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Improving the batch handling of the Container®-series line at Easy Sanitary Solutions

a company of Hansgrohe Group

ESS

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Improving the batch handling of the container-series line at Easy Sanitary Solutions

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Preface

Dear reader,

The bachelor thesis you are about to read is titled “Improving the batch handling of the container-series line at Easy Sanitary Solutions”. The research has been carried out as part of the graduation for the bachelor Industrial Engineering and Management at the University of Twente (UT). The aim of the thesis was to increase the production capacity (in terms of output) by improving the batch handling in terms of quality (quality issues) and quantity (batch sizes).

During my time at ESS, I have learned many new things and have gained many insights, both study-related and professional. Although it is a difficult and busy time for ESS because of the worldwide COVID-19 pandemic and the arrival of a new party, ESS gave me a place to complete my bachelor's degree. I really liked that I was welcome to come and perform my research physical at the production facility, despite the COVID-19 pandemic. I am grateful for the opportunity and trust the company has placed in me.

First, I would like to thank my supervisor at the company, Robert te Vaarwerk. As a former IEM student of Saxion, he precisely knew how to guide and give feedback. I would like to thank him for all his time and effort he spent on guiding me in my research. Although he was busy with his own work at the company and a pre-master, he always made time to guide and give feedback. Moreover, I want to thank him for the opportunity to help working on other (non-thesis) related projects within ESS. Besides Robert, I would like to thank all employees within ESS who have helped me collecting information

Thirdly, I would like to my UT supervisor Robert van Steenbergen. Without his valuable feedback and support, I was not able to finish my research. Besides, I want to thank Patricia Rogetzer for being my second supervisor and Ipek Seyran Topan for her support during the preparation phase of this thesis.

Finally, I would like to thank my family and friends for the support during my study and the execution of the research. Especially, I want to thank my buddy Nathan Hoogendoorn. Nathan helped me to be critical on my own work and stay motivated during the complete research process. The feedback I received from him really helped me improving the quality of my thesis.

Daniël Johannes Roelink

July 2021

Management summary

This research is performed at the production facility of Easy Sanitary Solutions (ESS) in Bad Bentheim (Germany). ESS is an international operating company in the market for sanitary solutions and sells many different products, including containers. The assembly line of these products is the line on which this research is focused on.

ESS became part of the Hansgrohe group by the end of 2020, stressing existing and bringing new challenges for the company. One of these challenges forms the base of this research: a too low production capacity of the container-series assembly line. Analyzing all the problems related to the low production capacity, three related problems were chosen and solved by answering the following research question:

> ***"Which batch sizes, insights in the quality issues and improvements to decrease the number of quality issues seen at the line can be introduced to improve the problems related to the batch handling and, with that, the production capacity of the container-series line at Easy Sanitary Solutions (ESS)?"***

To give insights in and analyze the current cycle times of the products of the container-series line, a tool has been created in Excel using Visual Basic for Applications (VBA). This tool was created for four goals, with the main goals being (1) using it in the batch size determination process and (2) giving ESS a tool to evaluate the more optimal batch sizes themselves when the research is over. Analyzing the results of the tool, some conclusions regarding the completeness and quality of the data and the removal of outliers have been drawn. Moreover, it turned out that the cycle times of the laser orders are not reliable. Further analyzing the results, it has been concluded that the overall quality and completeness of the data is good enough to use the tool and the data both internally and in the rest of this research.

The cycle time tool is used to gather data to determine batch sizes for products representing four difficulty groups of the container-series line. The batch sizes were determined by mapping and investigating the pattern and relation between historical batch sizes and cycle times. The found batch sizes were, in turn, compared with batch sizes considered optimal for other parts of the process. Combining the batch sizes ideal for these other parts with the identified batch sizes in the data, batch sizes both optimal for the station (i.e., reduce cycle times) and for the other parties of the production process were identified. Comparing the proposed batch sizes with the current product-specific average cycle times (using a weighted difference), a decrease of respectively 15.4%, 13.9%, 0.0% and 19.3% in cycle times in the four products groups has been realized.

The proposed batch sizes were validated using a sensitivity analysis. This sensitivity analysis showed that small changes in certain factors do not affect the batch sizes, cycle times and weighted differences of the cycle times of each group heavily. Moreover, it has been concluded that batch sizes close to the proposed batch sizes could be used and will have limited effect on the reduction in cycle times.

The quality part of the research starts with giving insights in the current quality issues seen at the container-series line by the creation of a tool in Excel using VBA. Using the results of the tool, an analysis of the quality issues has been executed and conclusions regarding the performance, both overall and per supplier, have been drawn. Moreover, the following other important conclusions have been drawn:

- [redacted] Censored
- There are some frequently occurring reasons, both per component and per supplier;
- The rejection rate for colored components is about the same as components without color.

Besides, the analysis resulted in some improvement points in the procedure of tracking quality issues, with the most important ones (1) always mention a reason for rejection and (2) add the discovery place in production facility.

The last subject of the research is to identify solutions to encounter fewer quality issues at the line as these result in more costs and variability in production time (cycle times) than quality issues encountered elsewhere. Using a brainstorm session and combining this with own solutions, twelve possible solutions have been identified. Based on an analysis of these solutions, the following six solutions have been selected to work out further in an implementation plan:

1. Capture and standardize quality assessment procedure of the goods receipt;
2. Capture requirements of components/products;
3. Tools for checking quality;
4. Move more responsibility to suppliers;
5. More frequent contact with suppliers;
6. Reconsider and change suppliers.

It is believed that the combination of these six solutions will have the most impact against the lowest costs. The implementation plan describes the steps, responsibilities, planning, evaluation measures, the costs and benefits and potential increase in production capacity. These last two shows that about €19,000 on quality issues can be saved and, simultaneously, 959 more products per worker can be assembled in the next three years when implementing the solutions.

Based on the research and other experiences during the research, recommendations have been deducted. The main recommendations are as follow:

- Perform analysis of cycle times and quality issues more frequently (for example using the two created tools);
- Use the proposed batch sizes as a decrease in cycle times of 12% is expected. A similar procedure could be applied to products not analyzed.
- Implement the six solutions using the implementation plan as an expected saving of about €19,000 and an expected increase in production capacity of 959 products could be realized in the next three years.

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Reader's guide

1. Introduction

The first chapter of the thesis introduces the reader to the company and the products the company sells. Moreover, an introduction to the problem and the approach is given.

2. Current situation

The second chapter describes the current situation of ESS. It starts with a description of the production facility. Next, the process of the assembly line this thesis is focused on is explained. The aspects considered in the current determination of batch sizes are then treated. Lastly, the process of the goods receipt is treated in more detail. All corresponding process flows are depicted in Appendix B.

3. Current cycle times

This chapter describes the tool that has been built to give insights in the current cycle times. It starts with a description of the approach and a literature study to the best way of visualizing data and a study to the detection and handling of outliers. The theory is used in the creation of the cycle time tool, of which a short description is provided here. A more detailed description of the tool can be read in Appendix C. Lastly, the results from the cycle time tool are depicted and analyzed.

4. Batch size determination

The process that is taken to determine batch sizes that reduce cycle times is described in this chapter. The chapter starts with the approach and some literature studies to gather knowledge needed in the determination process. Subsequently, the revised approach is described, including the factors and products from which the batch sizes are determined. The real measurements and determination is described afterwards. Lastly, a sensitivity analysis is performed to validate the results.

5. Current quality issues

The fifth chapter focuses on the tool that has been constructed to give an insight in the quality issues. First, the approach and necessary literature are described. Next, a short description of the tool is provided including some screenshots. A more detailed description of the tool is given in Appendix E. The chapter concludes with the results and an analysis of these results.

6. Quality issues at the line

Chapter 6 elaborates more on the steps that are taken to identify solutions to encounter fewer quality issues on the assembly line. First, the approach is described as well as the literature needed. The next section elaborates more on the solution design and includes the identification of criteria, solutions and an analysis of these solutions. The chosen solutions are then described and worked out more detailed in an implementation plan, with which the chapter concludes.

7. Conclusions, recommendations and discussion

The seventh chapter contains the conclusion of the research. Moreover, both subject-related as non-subject related recommendations are provided. This chapter ends with the discussion including limitations of the result of the thesis.

8. Reference list

The last chapter of the thesis contains a list of references that are used during the executing and writing of the thesis.

A. Full explanation problem cluster

The first appendix provides a detailed explanation of the problem cluster to familiarize the reader with all the problems the company faces regarding the production capacity of one of their lines.

B. Flow diagrams of the processes

Appendix B contains the process flows that has been constructed as part of the current situation described in Chapter 2. The process flows of the production facility, container-series line and goods receipt are shown.

C. Description cycle time tool

A more detailed description of the tool that has been made to give insights in the current cycle times is provided in this appendix. Moreover, screenshots and results are provided to give the reader an impression of the constructed tool and the results.

D. Batch size determination

The fourth appendix contains extra information regarding the batch size determination process. First, an overview of all products and orders from which batch sizes are determined is provided. Next, the manually measured laser times and the purchase quantities are provided. In addition, information regarding the finished goods warehouse, stock of finished goods and the demand for the finished products is provided. Lastly, tables showing the results of the sensitivity analysis performed on the proposed batch sizes are provided.

E. Description quality issues tool

Appendix E contains a description of the tool that has been constructed to give an insight in the quality issues. To give the reader an impression of the tool, screenshots are provided at the end of this appendix.

F. Quality issues at line

The last appendix starts with a list of possible solutions identified to encounter fewer quality issues on the line. Afterwards, more (background) information about the planning is provided. Lastly, the most important assumptions used during the cost-benefit analysis and potential increase in production capacity have been summarized.

List of acronyms & definitions

Acronyms

ATO	Assemble-to-order
B2B	Business-to-business
EPQ	Economic Production Quantity
ERP	Enterprise Resource Planning
ESS	Easy Sanitary Solutions
IQR	Inter Quartile Range
KPI	Key Performance Indicator
LB	Lower Bound
MTS	Make-to-stock
Q_n	n^{th} quartile of a dataset
R&D	Research & Development
SQD	Supplier Quality Development
SQM	Supplier Quality Management
TQM	Total Quality Management
TOC	Theory Of Constraints
UB	Upper Bound
VBA	Visual Basic for Applications
VSM	Value Stream Mapping
WIP	Work-In Progress
WMS	Warehouse Management System

Definitions

Batch size	The number of products that is assembled/produced in one order.
Cycle time	The average time it cost to assemble a product, including the process and setup time.
Key Performance Indicator	Important measures to determine the progress towards the determined goal. Based on KPIs, the right follow-up actions can be taken. Besides, KPIs are also used for benchmarking the performance with other companies.
Quality check	A set of steps to check the quality of products and ensure the process capabilities.
Quality issue	Any quality problem as a result of which the requirements and high-quality expectations of the customers are not met. Examples of quality issues are scratches, non-conform color, sharpness, straightness and leak.
Supplier Quality Management/ Supplier Quality Development	Set of activities to improve the performance of the suppliers of a company.
Theory Of Constraints	A methodology that systematically can be used to manage and improve processes by viewing an organization as a chain.
Total Quality Management	Set of activities that all stress the importance of integrating the idea of quality in the complete organization.
Value Stream Mapping	A lean method that helps identifying waste (non-value-added activities) by mapping the complete production process.

1. Introduction

This first chapter introduces the reader to the research performed. Section 1.1 contains a description of the company. Section 1.2 introduces the products that are assembled on the container-series line. In Section 1.3, the problem identification is described in which the core problem is selected. Section 1.4 provides an overview of the research design. Lastly, Section 1.5 provides an overview of the most important conclusions of this chapter.

1.1 Company description

Easy Sanitary Solutions (ESS) is an internationally operating company in the market for sanitary solutions. The company was founded in the small Dutch village Losser in 1928, where it started as a family company named Keizers. The family company started to design, produce and sell sanitary solutions with the aim of improving the life of the customer (Easy Sanitary Solutions, n.d.-a). Nowadays, ESS is located in both the Netherlands and Germany.

The aim of ESS is to create stylish and barrier-free bathrooms for everyone. ESS is the inventor, developer and official supplier of the Easy Drain shower channels (Easy Sanitary Solutions, n.d.-a). Besides this product, ESS also produces other kinds of products. The main product categories are shower drains, design drains, point drains, shower boards, wall niches and waterproofing. ESS produces and sells these products to other companies, like wholesalers and bathroom stores. These companies, in turn, sell and install the products of ESS to the final customers. Therefore, ESS is an "business-to-business" (B2B) company.

ESS designs, develops and produces over a million bathroom products each year. Based on the preferences of a customer, products with special dimensions, features or colors can be produced. The products are exported to and sold in over 40 countries in the world. Design, innovation, sustainability and high-quality products are main pillars for ESS (Easy Sanitary Solutions, n.d.-a).

Figure 1-1: Logo of Easy Sanitary Solutions (ESS). Source: internal.

At the end of 2020, Easy Sanitary Solutions B.V. has sold the majority stake to Hansgrohe SE. With this sale, ESS became part of the Hansgrohe group (Easy Sanitary Solutions, 2020). The Hansgrohe group is an international corporation with main brands AXOR & hansgrohe and is active in the field of bathroom and kitchen products. ESS is confident that this investment is positive for both Hansgrohe and ESS (Easy Sanitary Solutions, 2020).

The research will be conducted at the plant location in Bad Bentheim (Germany) and focuses on the assembly of the container-series (assembled on assembly line 5). More information about the products assembled on this line will be given in the next section.

1.2 Products container-series line

This section provides an impression of the products assembled on the container-series line. The container-series consist of different products that can be built in walls to store and hide bathroom items like shampoo dispensers. This enhances the bathroom design and gives an easy way to store bathroom items. The products can be categorized in ten different styles, each style having its own design. In Table 1, each style including a short description of the style is listed (Easy Sanitary Solutions, n.d.-b).

Table 1: Overview of the different products assembled on the container-series line (source: Easy Sanitary Solutions, n.d.-b).

Style	Description
BOX	Built-in bathroom wall storage solution, suitable for solid & dry walls.
T-BOX	Box with built-in tileable door to accommodate bathroom accessories, with push-to-open function.
C-BOX	Frameless colored box.
F-BOX	Box with a sophisticated frame to further improve the design of bathrooms.
W-BOX	Box with wooden frame made of solid oak.
T-ROLL	Product to store bathroom accessories (toilet brush or paper) with a tileable door.
V-BOX	Integrated tileable solution to hide water shut-off valves.
S-BOX	Solid surface box with white finish.
ROLL	Product to store bathroom accessories (toilet brush or paper), available in one finish and different designs.
SHELF BOX	Wall shelves suitable for storing items, can be placed anywhere indoors or outdoors.

Figure 1-2 shows a selection of the products assembled on the container-series line. Each style from Table 1 can be ordered in different dimensions, finishes, frames and options. A simple calculation to the number of different combinations reveals that, in theory, 1,165 different combinations are possible. In reality, some combinations do not occur frequently and are considered as customized products.

The products produced on the line are luxury products. In general, customers are willing to wait on these products but expect high-quality products. Therefore, delivering high-quality is really important and is major focus for ESS (and cost reduction is not). The products are typically produced Assemble-to-order (ATO). The faster flowing products, however, are often produced Make-to-stock (MTS).

A lot of different combinations, however, are still demanded (and produced) relatively frequently. This large number of different products leads to the fact that the container-series line has problems with the capacity and many (different) other problems. Inside ESS, this line is often seen as a bottleneck due to these problems. Because of the many problems that play with respect to this line, the (limited) capacity of the line decreases even more. Therefore, ESS has asked to investigate these problems more thoroughly and propose solutions to the most important ones.

Figure 1-2: Examples of products that are assembled on line 5, the container-series line. The products displayed in the figure are respective Box (no options), T-Box, V-Box, Box (large dimension & mirror option), C-Box and T-Roll (TCL-8) (Easy Sanitary Solutions, n.d.).

1.3 The problem

This section introduces the problems in the thesis. First, the starting problem is explained. Next, the problems that will be solved in the thesis are identified. Lastly, the measuring of the problems is explained.

1.3.1 Research motivation & action problem

In 2020, the assembly process of all assembly lines are digitized using a custom SAP (Enterprise Resource Planning, ERP) Web-app, named AssemblyPro. This enables the individual assembly lines for planned orders to see, start/pause, report quality rejections, print labels and book the finished items to the stock. This means that there is a lot of data available to perform analysis on. Until this moment, this data is not used to give great insights into the current performance and to optimize the assembly of the container-series line. Short periodic data analyses about the performance of the line are already done. In combination with the feeling of some stakeholders within ESS, it is known that the container-series line underperforms compared with the other assembly lines. The exact numbers and reasons, however, are unclear.

Censored

[redacted] In particular for the container-series line, it is expected that the line will be under even more pressure to perform better because it already underperforms (in terms of output) in the current situation. Therefore, it is important that the performance of the line will be increased by investigating the problems that play on this line.

Thus, the problem the company faces relates to the production capacity of the container-series line. With the production capacity, the performance (i.e., the number of products that is assembled) on the line is meant. According to Heerkens and Winden (2017, p.22), an action problem "is a discrepancy between the norm and the reality, as perceived by the problem owner". Comparing norm and reality, there is a discrepancy between these two and, thus, an action problem can be identified. The action problem for the thesis has been defined as:

> ***"The container-series line of Easy Sanitary Solutions (ESS) has a too low production capacity, while the capacity must be larger to keep up with the rising demand the company faces."***

1.3.2 Problem identification

To identify the root of the action problem, the core problem, a problem cluster has been made. A problem cluster is a figure depicting all the problems with their inter-relation(s) that play with regard to an action problem and is a good tool to identify the core problem (Heerkens & van Winden, 2017). The constructed problem cluster for this thesis can be seen on the next page in Figure 1-3. In this cluster, the action problem is placed at the right side (shaded grey) and the problems influencing this problem at the left side. These problems are identified after working for a short period in the production and performing interviews with the involved stakeholders.

The problem cluster shows that there are many problems causing directly and indirectly a low production capacity of the container-series line. Five categories of problems can be identified, these are: R&D, complexity, batch, component and batch handling. The problems within these categories are explained in more detail in Appendix A.

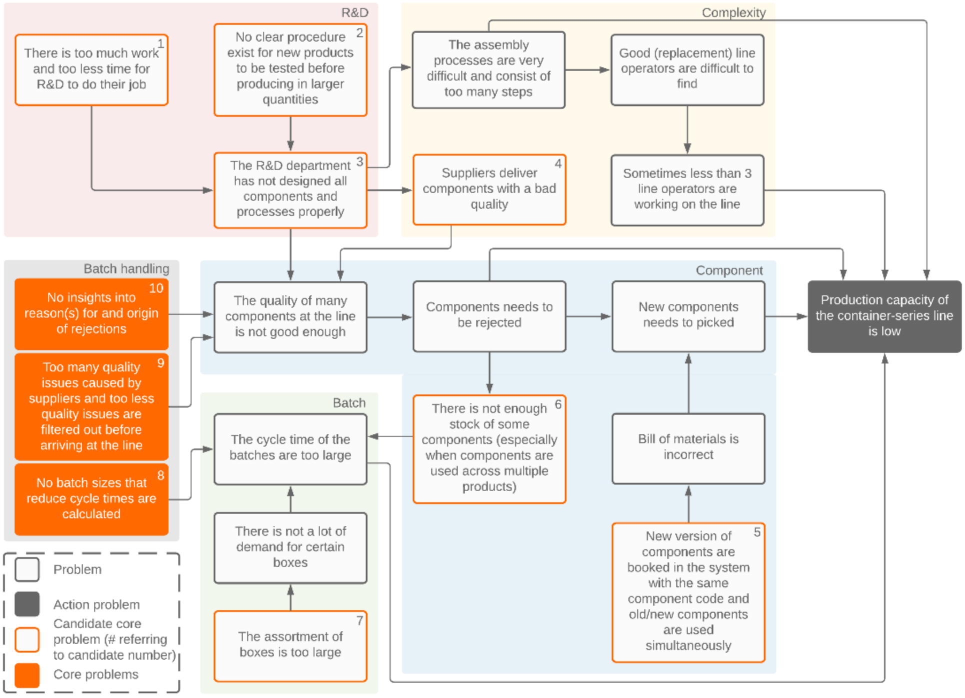


Figure 1-3: Problem cluster containing problems that play with respect to the action problem of "a low production capacity of the container-series line".

1.3.3 Core problem selection

To identify the core problems from the problem cluster (Figure 1-3), the "rules" for identifying core problems of Heerkens and Winden (2017) have been used. The candidate core problems are the problems in Figure 1-3 with an orange border, including the three problems completely marked orange in the category "Batch handling". All of these candidates are problems at the end of the cluster (i.e., no cause-problem can be identified), except for numbers 3 and 4. The reason for this is that it is believed that when the cause-problem(s) is/are solved, then the problems are still not fully solved. Because of that, these problems are also considered as candidates for the core problem.

To select a core problem, the candidate core problems have been investigated more thoroughly. By interviewing stakeholders within the company and having discussions with the company, the majority of candidate core problems have been excluded from being a core problem. The problems and reason(s) for exclusion are summarized in Table 2.

Table 2: Overview of the core problem selection process, including reason for rejection and notes.

Candidate number	Reason for exclusion as core problem	Note
2	*Censored*	[redacted]
3	Under construction by another graduate IEM student within ESS.	X
4	Influence on this problem is limited.	It is recommended to look to this problem themselves.
5	(1) Easily solved by just putting an A or B behind the code; (2) already applied and worked well.	X
1 & 7	Influence on these problems is limited and can be solved relatively easy.	Can be solved by cutting in the assortment or hire extra employees for R&D.

Analyzing the candidates and excluding most of them, a couple of candidates are left. These candidates left are the problems within the category batch handling (number 8, 9 & 10) and the problem of not having enough stock (of some) components (number 6). In case multiple problems can be considered as core problem, Heerkens and Winden (2017) propose to choose the problem that has the greatest effect against the lowest cost when solved.

In cooperation with the company, it is decided to tackle all problems within the category batch handling because these problems are interconnected and when solved, are expected to have a major impact on the production capacity of the container-series line. Besides, by giving more insight in the quality issues (candidate number 10), ESS can assess which suppliers perform good and which less. Indirectly, this can help to solve candidate core problem 4 as well.

1.3.4 Measuring the core problem and norm & reality

To measure the effect of the proposed solutions, the core problem must be (made) measurable. The batch handling itself cannot be measured directly. To quantify the effect, the batch handling is measured using two variables: the batch quality and batch quantity. These variables are operationalized using indicators to make the variables measurable (Heerkens & van Winden, 2017).

Batch quality

The batch quality variable can be measured using the indicator "percentage of orders that contains one (or more) quality issue(s), encountered on the line". A quality issue mentioned here means that a component must be rejected because of a quality problem, which could be a scratch, non-conform color or wrong dimensions. It consists of quality issues coming from two sources: (1) quality issues caused by suppliers (and during transport) and (2) quality issues occurring during the whole assembly process (e.g., picking, warehouses and assembly).

The focus of this research lies on reducing the number of quality issues on the line by giving insight in quality issues and other additional solutions. As the process is not viewed in terms of content, the quality issues encountered at the line and made during the assembly process will not be considered and, therefore, not decrease. The other source of quality issues, the issues made by suppliers, will be affected by the solutions. With the effect on this type of quality issues, the total percentage will also be affected and, with that, the (overall) quality of the components.

Batch quantity

The batch quantity variable can be measured using the indicator "average cycle time reduction per product (in %)". The indicator measures the decrease of average cycle time in percentage i.e., the time it takes for a product to be assembled (cycle time) before and after the use of the newly proposed batch sizes. To calculate the reduction, the production data (including cycle times) of the last six months can be taken as this is seen as a period long enough to be able to draw a conclusion about the reduction. The cycle time of an order starts when the employee responsible for starting the order starts the order on the tablet and does the first action: the worker picks the components from a pallet and puts these on the table for a first quality control. It ends when all the assembled products are packed in boxes on (a) pallet(s) and the order is marked as finished in the system (i.e., there is no further touching on the line). When the batch sizes will be optimal, this average cycle time will decrease and thus the batch handling will be better.

To be able to attach an expected reduction percentage to this variable, the products on the line are divided in four different product groups based on a self-constructed difficulty score. It is expected that products within a group will have approximately the same reduction percentage. This difficulty score measures how difficult it is for ESS to assemble a product and is calculated using five criteria: style, dimension, finish, frame and option (LED, mirror or door). Based on the characteristics of a product, a score of 0 or 1 is given for all criteria except for the option. Each of the criteria represents a criterion which makes assembly of a product more difficult. Relatively simple styles, dimensions, finishes or frames get a 0 score, the more difficult styles, dimensions, finishes or frames get a 1 score. The option criterium is measured on a 0 – 3 scale, based on the number of options on a product (e.g., zero options scores a 0, two options scores a 2). The scores of all criteria are summed up and a final score is calculated. Using this final score, the product can be divided into four different groups: basic (score 0), simple (score 1), medium (score 2) or difficult (score 3+). Table 3 depicts this scoring principle.

Table 3: Scoring principle to divide the products in four groups, based on difficulty of assembly.

Criteria\Score	0	1	2	3
Style	C-BOX, BOX, S-BOX, SHELF BOX, T-ROLL (TCL-14|15), ROLL (TCL-2|3|4)	F-BOX, T-BOX, W-BOX, V-BOX, T-ROLL (TCL-8|9|10|11), ROLL (TCL-1|5|6|7)	X	X
Dimension	15 x 30; 30 x 30; 60 x 30	90 x 30; 120 x 30	X	X
Finish	No color (stainless steel)	Other colors (Anthracite, Black, White, Creme)	X	X
Frame	No frame	Frame	X	X
Option	No option	1 option	2 options	3 options

Norm & reality

The variables and indicators are summarized in Figure 1-4. Together, these indicators and variables account for the full 100% of the core problem, the batch handling. This means that the method of decomposing variables is used (Heerkens & van Winden, 2017).

Performing a small data analysis and in cooperation with the company, it is decided to estimate the reality for the percentage of orders that contain quality issues encountered at the line at 22% and the norm at 17%.

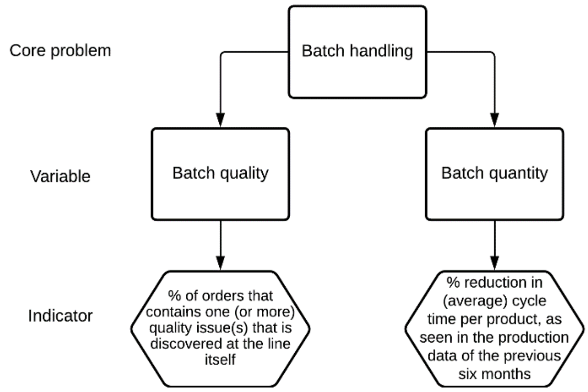


Figure 1-4: Overview of the core problem, variables and indicators.

Furthermore, it is expected that the decrease in cycle time will be different for the different groups because of three reasons:

1. Easier products will be assembled more often and less reduction can be achieved in these cycle times with only batch size changes;
2. Difficult processes have more and more complex assembly steps. As the optimal batch sizes will result in more steps, the cycle time is reduced more;
3. More difficult features are more sensitive for quality issues. For example, a colored product is more sensitive for scratches than a normal non-colored finish.

In cooperation with the company, an expected decrease in the cycle time (seen in the production data of the previous six months) have been set of 10%, 10%, 15% and 20% respectively for the basic, simple, medium and difficult group. The overall average reduction in cycle time is about 14%.

1.3.4.1 Formal definition core problem

The formal core problem for the thesis has been defined as:

> ***"For the container-series line of Easy Sanitary Solutions (ESS), there is no insight in the quality issues, too many quality issues happen at suppliers and too less are filtered out before arriving at the line and there is no use of batch sizes that reduce cycle times; which all limit the production capacity of the line. It can be measured using two variables: (1) batch quality; 22% of orders contain quality issues and are encountered at the line while the norm is 17%; and (2) batch quantity; average cycle time reduction (different for the different product groups) with an overall average of about 14%."***

1.4 Research design

The research will be focused on two main subjects: batch sizes and quality issues. Both subjects are believed to have a major influence on the production capacity and, therefore, both treated equally in this research. To solve the core problem, a main research question has been defined and is as follows:

> ***"Which batch sizes, insights in the quality issues and improvements to decrease the number of quality issues seen at the line can be introduced to improve the problems related to the batch handling and, with that, the production capacity of the container-series line at Easy Sanitary Solutions (ESS)?"***

In order to answer this question and structure the research, three sub research questions are defined. Each sub research question can only be answered after the right knowledge is gathered. Because of that, each sub research question is accompanied by multiple knowledge questions:

1. **What is the current situation of the (production) process of ESS?**
    i. How is the production facility and, more detailed, the container-series line and goods receipt currently organized?
    ii. Which elements are currently considered in the current determination of batch sizes?
2. **Which tool can be developed to give more insight in and analyze the current cycle times?**
    i. According to literature, what is the best way to present and visualize data?
    ii. From literature, how can outliers in a dataset be detected and handled?
    iii. What is the current situation regarding the production capacity, in terms of cycle times and worker count?
    iv. Which conclusions can be drawn from the results of the analysis of the cycle times?
3. **Which batch sizes reduce cycle times for the container-series line (disregarding quality rejections), considering factors identified in the practice and literature?**
    i. Which methods exist and are commonly used in literature to determine batch sizes?
    ii. From literature, which aspects can be identified that influences the calculation of batch sizes considering an isolated station?
    iii. Which factors can be identified that influences the calculation of batch sizes considering the total process?
    iv. Which sensitivity analyses exist and how can it be applied to the proposed batch sizes?
4. **Which tool can be developed to give ESS more insight in and analyze the current occurring quality issues?**
    i. Which quality problems do currently occur at which suppliers and what is/are the reason(s) for this?
    ii. Which conclusions can be drawn from the insights in the quality issues?
    iii. Which other recommendations can be recommended regarding the analysis of the quality issues?
5. **Which actions and improvements can be introduced at ESS to ensure the quality of components at the line?**
    i. Which theories are available in the literature about quality-related issues and can be used to ensure a high quality of components during the process?
    ii. What criteria can be identified that the solutions must meet in order to work properly?
    iii. What effects in terms of costs and production capacity are realized through the improved quality assessment procedure?

The following deliverables of this thesis have been defined:

- ✓ Insight in and conclusions about the current production capacity in terms of cycle time(s) in relation to current batch sizes and worker count.
- ✓ Batch sizes of products that reduce cycle times, considering the complete production process and aspects identified in the literature.
- ✓ Insight in and analysis of the reasons for the quality issues that occur at which suppliers and where improvements can be made.
- ✓ Actions and procedures to guarantee the quality of components at the line and, with that, lower the number of quality issues encountered at the line itself.
- ✓ Additional recommendations identified while conducting the research.

1.5 Conclusion

This chapter introduces the reader to the company and problem. Easy Sanitary Solutions (ESS) is an internationally operating company in the market for sanitary solutions and produces may different products. One of their assembly lines, the line producing the containers, is the focus of this research. The action problem with which this research started is the low production capacity of the container-series line. Investigating all problems that cause this problem, a core problem has been selected: poor batch handling at the container-series line. This core problem consists of three subproblems: (1) batch sizes that reduce cycle times are not calculated and used, (2) there are no insights in the quality issues and (3) too many quality issues happen at suppliers and too less are filtered out before arriving at the line. With the help of two variables and indicators, these problems are made measurable.

2. Current situation

This chapter contains information about the context of the research performed at Easy Sanitary Solutions (ESS). The current situation is described to gain more knowledge about the current way of working of ESS. Section 2.1 describes the layout of and material flow in the production facility. In Section 2.2, the process of the container-series line is visualized and explained. The current quantity and quality assessment procedure of the goods receipt is explained in Section 2.3. The factors used to determine the current batch sizes are described in Section 2.4. Lastly, Section 2.5 summarizes the conclusions of this chapter.

2.1 Production facility

The layout of the production facility is displayed in Figure 2-1. The production facility is arranged in such a way that the flow is from left to right. The layout of and the flow throughout the production facility will be explained in this subsection. This explanation and visual overview is created from information received during multiple tours throughout the production facility and by performing both interviews and observations.

Censored

Figure 2-1: Overview of the layout of the production hall.

ESS has a total of fourteen assembly lines, divided over two different but connected halls. Workers on assembly lines 1-10 manually assemble the products ESS sells. Each assembly line is specialized in assembling products of a certain product line. Line 5, for example, only produces products of the container-series line. At assembly lines 11-14, workers manually assemble the accessories that are delivered along the products. Almost all components used at the lines 11-14 are stored along the lines and can be picked by the workers themselves. It is decided to place these components along the lines as these components are not of high-value (C-items according to the ABC analysis), are bulk components and the frequency of use is high. As no pick action from the components warehouse is required for the components that are stored along the line, the components will be written-off when an order is finished. This write-off process is called "backflushing". When an order of accessories is finished, the accessories are packed in boxes and brought to the hall with the other assembly lines. These accessories are stored, in turn, along lines 1-10 as these are used with a high frequency when packing the boxes (e.g., almost all products have at least one accessory).

The other components that are needed at assembly lines 1-10 are divided into two categories: (1) cheap bulk components and (2) components that need to be picked. This first category of components is positioned along the lines as these are frequently used in large numbers and do not represent a high value (for example screws). The workers can easily pick these components themselves when required. The second category consists of components that need to be collected from the components warehouse and delivered. The instruction for collecting is sent to the pickers (see below) and is called a "pick order". These pick orders will be picked from the components warehouse and, when picked, transported by the internal supplier (i.e., forklift driver). Before components are stored in this warehouse, the components need to be delivered by suppliers. This process will be discussed in the next subsections. An overview of the complete process is provided in Figure B-1 in Appendix B.

2.1.1 Goods receipt

[redacted] *Censored* [redacted] The flow through the facility starts at the goods platform (upper left corner in Figure 2-1), where the components are delivered by suppliers. The pallets or boxes containing components are unloaded by the truck driver itself, which puts the incoming components near the door between the goods platform and the components warehouse. The components are transported by forklift to the goods receipt hall by one of the goods receipt workers.

At the goods receipt hall, an order is chosen that will be booked in the system. All pallets of an order are checked separately on both quality and quantity. The quantity and quality check are explained in more detail in Section 2.3.1 and 2.3.2. If all pallets are checked, the correct number of components are booked in the system. Here, correct means that only components that are actually delivered and have a good quality are booked in the system. For all pallets of the order, an identification sticker including scannable code is printed and attached.

If extra (pre-)processing is needed, an extra red sticker will be attached to the pallets and the pallets are transported to a special place in the goods receipt hall. If the (pre-)processing is done, a worker from the workshop places the pallets in the rack at the left bottom of the components warehouse in Figure 2-1. If no (pre-)processing is needed, the pallets are directly transported to this transport rack. An overview of the goods receipt process can be seen in Appendix B in Figure B-2 (and more detailed in Figures B-3 & B-4).

2.1.2 Components warehouse (picker)

The components stay in the rack until a picker selects the order on the scanner to put the components away. To find the right place, the picker scans the label which is placed on the pallets or boxes at the goods receipt. The components are then transported to the correct location and put away.

The components stay in the components warehouse until they are needed at one of the assembly lines. When an assembly order is scheduled, a “pick order” is created and placed on the list in the scanners of the pickers. There are three priority levels for a pick order: (1) within two hours, (2) before the end of the day and (3) low priority (normal scheduled orders).

Based on priority, a picker selects a pick order on the scanner through the WMS (Warehouse Management System) environment and the correct information is shown. The data originates from the database containing the scheduled orders (including priority). The selection of an order creates a data file containing the start time of a pick order and this will be stored in the ERP system. The picker then drives to the location of a component shown on the scanner and collects this component. Next, the picker confirms this on the scanner (in the WMS environment), which creates a data file stored in the ERP system. If the needed quantity cannot be picked, a shortage is booked in the system (and in ERP).

The following step is to check if all (different) components of an order are picked. If this is not the case, the process is repeated: the picker goes to the next location (shown in the scanner), picks/collects the next component and the quantity is checked and confirmed (and possibly a shortage is booked). If all (different) components are picked, the picker drives to the Work-In Progress (WIP) location, located at the right side of the components warehouse (see Figure 2-1), and delivers the component(s). The WIP location contains all picked orders sorted by line so it can be easily transported to the assembly lines when needed. The identification (order list) is printed and attached to the pallet(s) containing the components and the order is finished on the scanner. Figure B-5 depicts the process of picking a pick order by a warehouse picker.

2.1.3 Internal supplier

The internal supplier either (1) transports a picked order to an assembly line (only consisting of products that cannot be picked along the line) or (2) transports a finished production order to the put-away location (rack at the right side of the finished goods warehouse, see Figure 2-1).

The process of the internal supplier starts with deciding on the order that needs to be moved, which is communicated either manually (thirty minutes before a production order starts) or via the scanner (when an order is finished).

In case the internal supplier needs to deliver components for a production order, the needed pick order is communicated manually by giving the correct pick order numbers. Next, the internal supplier drives to the WIP location, picks the correct order(s) and transports these to the correct lines. When delivered, the production can start. The production process of the container-series line is explained more detailed in Section 2.2.

When an assembly order is finished, a label is attached to the pallet/products. Moreover, the internal supplier is notified by its scanner, this time for transportation to the finished goods warehouse. By selecting and scanning an order, the internal supplier gets the necessary information and transports the products to the rack of the finished goods warehouse (at the left side of the finished goods warehouse in Figure 2-1). Next, the order is booked as finished in the scanner in the WMS environment. This action updates the location of the order by creating a datafile in the ERP system and the order is deleted from the database containing the orders that need to be transported. An overview of the internal supplier process can be seen in Figure B-6.

2.1.4 Warehouse picker (finished products)

In the finished goods warehouse, a same system analogous to the put away process of the components warehouse is executed. The products that need to be put away (and thus in the rack) appear on a list on the scanner of the pickers in the finished goods warehouse. The products stay in this rack until a picker selects the order and brings the components to the right place in the finished goods warehouse. The picker delivers the products to the right location, which can be found by scanning the label.

2.1.5 Shipment of products

The last step in the complete process is the picking of the products that are needed for a shipment and packing them properly. A system analogous to the system used by the picker from the components warehouse is used. Based on priority, an order is chosen and collected using the scan system. When all products for one order are collected, the order is packed properly and provided with the right sending information. Two times per day, the orders will be loaded in a truck of a transportation company, which delivers the products to the right locations.

The research will be focused on assembly line 5: the container-series line. This line is positioned at the upper right corner of the hall containing the assembly line 1-10 (see Figure 2-1). To understand and explain the process on this line, an overview has been made. This overview and explanation is provided in the next subsection.

2.2 Container-series assembly line

To explain the process of the container-series line, a general process containing multiple subprocesses has been built. All the process flow models can be seen in Appendix B.2. These process models are based on observations and information received during an interview with the quality manager. Besides, the process flows have been verified by the production planner.

2.2.1 General process

The process starts with determining the next production order based on the schedule. The production orders that are scheduled (including priority) will be loaded from the scheduled orders database. The workers on the line manually notify the internal supplier thirty minutes before the order starts that components for an order are necessary and need to wait until they are delivered. When the components are delivered, the actual processing is started. Three types of orders can be distinguished and necessary for producing an item, these are: laser order, paste order and assembly order.

Only the last one is obligatory, the other two are optional. These types can only be executed in one order: (laser) – (paste) – assembly. The orders, however, do not have to be executed immediately after each other. The time in between a laser and assembly order can be multiple hours or even days (in case a paste order is executed in between, see Section 2.2.3). The time in between a paste and an assembly order, however, is always more than 24 hours so that the used glue can dry. An overview of the general process line can be seen in Figure B-7.

2.2.2 Laser order

A laser order starts with starting the order on the tablet, which creates a data file containing the start time and is stored in the ERP system. Next, the quality and quantity is checked. Afterwards, the correct mold is determined and it is determined if this one is already placed. If not, the correct mold is placed by the worker. If it is already placed, no action is needed to place the mold. The correct program for lasering is then determined and selected (if not already selected).

After the quality and quantity are checked and the machine is correctly configured, the lasering process can start. It consist of:

1. Picking of a component/product;
2. Remove the foil where the logo should be placed (or all foil for Hansgrohe products);
3. Placing the component in the mold;
4. Laser the logo in the component/product with the help of the machine;
5. Remove the component from the mold;
6. Check the quality of the lasered component(s);
7. Place the component on the finished components pallet.

The worker then checks if all components that need to be lasered are lasered. If this is not the case, steps 1-7 are performed again for the next component. If all components are lasered, the worker finishes the order on the tablet. This creates two data files: (1) a data file with the finish time (stored in the ERP database) and (2) a data file indicating that the order must be moved by the internal supplier (stored in the database containing all the move orders). The laser order process is depicted in Figure B-8 (and more detailed in Figures B-9 and B-10).

2.2.3 Paste order

The paste orders start with selecting the order on the tablet (which creates a data file in the ERP system) and a quality and quantity check. Afterwards, the same principle as the laser order is executed but now on the gluing machine: determining (and placing if necessary) the correct mold and program. Next, the gluing process can start. This process consist of six subprocesses:

1. Preprocess the components for one product (e.g., special foil or waterproof adhesive tape);
2. Remove foil and clean product;
3. Align the fronts (align correctly so that the fronts are straight);
4. Put glue on the component with the machine;
5. Manually press the components together;
6. Put the finished product on a pallet.

If not all products are glued, steps 1-6 are repeated for the next product. If all products are glued, the order is finished on the tablet and a data file is created for this finish time. The order does not have to be transported because the products are dried along the line. After the glue is dry, which takes 24 hours, the assembly order can start (see Section 2.2.4). An overview of the paste orders can be seen in Figure B-11 (and more detailed in Figures B-12 and B-13).

2.2.4 Assembly order

First, an assembly order is started using the tablet, which creates a data file containing the start time and is stored in the ERP system. Afterwards, the components are checked on quality and quantity. The picked components and toolboxes are then placed on the table simultaneously. Next, two processes are initiated (explained below): the assembly of the product and the assembly of the box.

The first one consists of (1) picking of the additional components, which can be picked along the line, so-called “grijp” components (C-components and accessories), (2) assembling the product and (3) performing an additional quality check. The assembly of the box consists of three processes: (1) folding a box, (2) attaching sticker(s) on the box and (3) picking and putting the accessories in the box.

The next step is to place the assembled product in the box and place this on the pallets with the finished products. If not all products are assembled, the assembly process of the product and of the box will be initiated again for the next product. If all products are ready, the order is marked as finished on the tablet. This creates two data files: (1) a data file with the finish time and (2) a data file showing the order that needs to be moved by the internal supplier, which are the same as mentioned earlier. The overview of the assembly order can be seen in Figure B-14 (more details in Figures B-15 and B-16).

2.3 Process goods receipt

This section explains the quantity (Section 2.3.1) and quality (Section 2.3.2) assessment process of the goods receipt more detailed.

2.3.1 Quantity check

The quantity of an order is checked to determine if a supplier really delivers the promised and paid quantity. Per pallet, one box is used to represent the quantity of the pallet. First, the number of components on the first layer, the number of layers in the open box and the number of boxes on a pallet are counted. These numbers are multiplied to get an estimated total number of components on a pallet.

If this estimated quantity is conform the agreements, no further actions are required. If the quantity is not good, either smaller or larger than agreed, multiple boxes of the pallet are detached and checked on quantity in the same manner as explained in the previous paragraph. The missing number of components is noted and is considered when booking the components in the system. Besides, the missing number is reported to the supplier for appropriate follow-up actions.

A final note of this subsection is that the quantity is only determined if it is possible practically. When bulk components are delivered (for example screws), these are not checked on quantity at all. The only thing checked in these cases is if it is reasonable that the order contains the ordered quantity. If it is reasonable that the box contains the ordered quantity (among others based on the size), it is assumed that the correct quantity is delivered. An overview of the quantity check is provided in Figure B-17.

2.3.2 Quality check

The quality of the incoming components is checked to determine if the quality of the components are according to ESS standards (among others ISO 9001). First, the sample size (i.e., the number of products that is checked) is chosen. The sample from one box represents the quality of the pallet. Normally, about 3-5 products per box are checked.

Next, a random product from the open box is picked and the dimensions are measured using a measuring tape. These measured dimensions are compared with the norms, which can be read in the shipping documents sent along the pallet. Then, a visual check is done on the quality of the component. More specifically, the goods receipt worker visually checks the component on color, scratches, contamination and other visual deficiencies (i.e., completeness). Besides, the edges of the components are checked by feeling the edges to determine if these are not too sharp. Afterwards, the straightness of components is checked by (1) a visual inspection and (2) by checking it on a straight surface. Currently, no requirements of the components and allowed quality issues in the components are captured. The assessment is solely based on the experience of the goods receipt workers.

Afterwards, multiple scenarios can occur based on the results of the check:

1. **The dimensions, visual quality and straightness are all sufficient.** If all components within the sample are checked, the process is ended. If not all components are checked yet, the complete quality check is repeated for a new component.

2. **The dimensions or visual quality or straightness is/are not sufficient.** If one of the aforementioned criteria is not good, multiple components from the same box are checked to determine if the quality issue also occurs in the other components from the box. Besides, multiple other boxes are detached and undergo the quality check as explained to determine if these other boxes also contain components with a quality issue. If this check is over, the number of components with a quality issue is noted and is considered when booking the components in the system. Thereafter, the components with a bad quality are transported to the rejection area (a special location with the goods receipt), where the quality manager does the same check again and initiates the appropriate follow-up actions.
3. **It is not sure if the dimensions or visual quality or straightness is/are sufficient.** In this case, the quality manager is contacted and his opinion about the quality issue is asked. If the quality manager thinks the quality issues are minor, do not form a problem in the process or are still conform the standards of ESS, the components are marked as good quality and the rest of the procedure of scenario 1 is executed. In case the quality manager thinks that the quality issues are major, the rest of the procedure of scenario 2 is executed.

Figure B-18 contains an overview of the quality check at the goods receipt.

2.4 Batch sizes

The production planner is the person responsible for making the production planning and the determination of the batch sizes. The production planner determines the batch size for a production order based on his own feelings. These feelings are derived from his own experience and substantiated with certain aspects. After performing an interview with the production planner, the following aspects considered are identified:

- **Customer orders.** When the order of a certain product has to be scheduled, the already placed customer orders are considered when determining the batch size. If, for example, already ten products of a certain product are already ordered, the production planner tries to plan a batch size of equal to or greater than ten (only if possible considering the other aspects).
- **Demand.** The second aspect, demand, is the quantity of a product demanded by customers. It is derived from two sources:
    1. *Historical demand:* The demand of the period in the previous years.
    2. *Forecasted demand:* The expected demand for the coming weeks and months.

  Combining these components, the expected customer demand can be identified and used in the production schedule and batch sizes. When determining the batch sizes, this aspect is probably one of the most important factors as ESS tries to deliver products within three weeks.
- **(Usual) purchase quantity.** When a product is usually sold in certain quantities, for example in quantities of fifty, only batch sizes of (multiples of) fifty are scheduled. Sometimes, somewhat larger batch sizes are made to also incorporate the single sale of the product.
- **Capacity of the assembly line.** The capacity of an assembly line (i.e., the number of products that can be made) is limited and needs to be used to assemble all products of a certain product line. When the assortment of products assembled on a line is large, the capacity of a line must be divided over many different products and only small batches can be planned.
- **Stock of components.** This aspect limits the size of the batch sizes, as some components are often not or very limited in stock. Components are not stored in larger quantities as the space in the components warehouse is limited and the assortment of different products is large, with each product having its own components. Especially for products in which components are used that are shared among multiple products, this aspect is the limiting aspect. These components cannot be fully attributed to one product, as otherwise the other products cannot be assembled. Besides, a small number of these components must also be kept in stock, to handle variability in customer orders.
- **Stock of finished products**. The safety stock and the quantities in the finished goods warehouse is also considered when determining batch sizes. Safety stock of some product must be kept to deal with uncertain customer demand. Besides, the space in the finished goods warehouse is limited. When the capacity in the finished goods warehouse for a certain product is reached, smaller batch sizes will be planned or the order will not be scheduled at all.

2.5 Conclusion

This chapter described the context in which the research is performed. By having multiple tours through the facility, working at different stages of the process and performing interviews, a better understanding of the current situation has been created. First, the complete process of the production facility has been described and visualized. Next, the processes of both the container-series line (consisting of the three order types: laser, paste and assembly) and the goods receipt have been described. Among others, it has been identified that there is no standard goods receipt process and that the assessment of the quality of components is based on the experience of the goods receipt workers. Lastly, aspects used in the current batch size determination have been identified. These are: customer orders, demand, (usual) purchase quantity, capacity of the assembly line and stock of both components and finished products.

3. Current cycle times

This chapter describes the insight creation of the current cycle times of the container-series line. Section 3.1 describes the approach for the construction and the aim of the cycle time tool. The literature that is needed to construct the tool is described in Section 3.2. Section 3.3 provides a short explanation of the tool, including screenshots of the main screens of the tool. Section 3.4 contains the most important results of the tool. The results are analyzed in Section 3.5. Lastly, the conclusions of this chapter are summarized in Section 3.6.

3.1 Approach

To give insights in the current cycle times, a tool will be constructed that automatically calculates the cycle times. Besides, this tool contains visual elements to enhance analysis of the current cycle times. The tool will be constructed with the help of Visual Basic for Application (VBA) and Microsoft Excel. VBA is a language that is "effective and efficient when it comes to repetitive solutions to formatting or correction problems" (Microsoft, 2019). The tool will be made in such a manner that it can be used for all assembly lines of ESS but with main focus on the container-series line. Besides, the tool will be made flexible to be able to handle new data (e.g., data of other periods).

The goal of the insight creation is fourfold. First, it is to provide ESS with an easy way to see its current performance in terms of cycle times. Second, the current cycle times can be used to standardize, track and minimize cycle times. Moreover, the insight helps in the determination process of creating optimal batch sizes. Lastly, it helps to evaluate the effects of the optimal batch sizes in terms of cycle times reduction.

3.2 Literature

This section contains the literature that is needed to construct the tool that gives insight in the current cycle times. Section 3.2.1 provides information about the graph type that best visualizes certain data. Section 3.2.2 contains information about the detection and handling of outliers.

3.2.1 Chart types that best visualize data

According to Hink et al. (1998), there are two ways of visualizing quantitative data: numerical (tables) and spatial (graphs or charts). The chosen visualization must be aligned with the type of data as otherwise the visualization would not work (Shaheen et al., 2019). Besides, the goal and use of the data visualization by the user must be considered when deciding which visualizations to use (Gillan et al., 1998). Choosing the correct visualization is a difficult task about which a lot has been written in literature.

Gillan et al. (1998) have developed a flow chart that helps choosing a way to present quantitative data. Based on three criteria (amount of data, value of visualizing data and uses of data), a certain type of presentation is suggested. For graphical representation, Gillan et al. (1998) propose three guidelines that helps deciding for a specific form:

1. **Users experience**: it is suggested to use graphs with which the readers are probably already familiar with.
2. **Users needs**: based on the needs, a certain type of graph suits better than other types (see Table 4).
3. **Characteristics of variables**: a line graph can best be used to visualize continuous and ordinal variables, while a bar graph is suitable for categorical and ordinal variables.

Table 4: Best graph type per user need, as identified by Gillan et al. (1998).

Graph type	Users' needs
Line graph	Relative or absolute amounts; Rate of increase in mean; Interactions between variables.
Bar graph	Difference between means.
Pie chart	Proportions but not absolute amounts.
Scatter plot	Correlation between two variables.

Hink et al. (1998) performed an experiment to investigate which visualization works the best for different purposes. Multiple sorts of so-called "grables" are among the types of visualizations, which are graphs depicted with the corresponding numbers to enable the user to precisely read the value of a graph. The results show that displays with numbers (i.e., line grables, bar grables, pie grables, and tables) result in more accurate responses, somewhat higher response time (only grables) and lower error rates than the other types of displays (Hink et al. 1998). Furthermore, a bar grable is best for visualizing comparisons and tends, while the line grable is best for visualizing numerical values. Lastly, pie charts score the least accurate responses but appeared to be good to visualize trends.

Chynal and Sobecki (2016) used an experiment to evaluate the performance of different charts. By answering different questions and recording the eye movement of the participants, some performance measures could be measured and compared for the different graph types. Although a very small research population is used, the research does have some interesting findings regarding the most suitable graph type. Comparison of values can best be done using a column chart, while comparison of charts using "synchronized charts" (Chynal & Sobecki, 2016). Trends are best visualized using a line chart and large datasets using drilldown tree maps. Lastly, a pie chart is suitable for both drilldown data and percentage values (Chynal & Sobecki, 2016).

To investigate which visualizations are the best for certain data, Shaheen et al. (2019) combined a literary study with experiments to validate the results found in literature. Shaheen et al. (2019) argue that categorical data can best be represented using a column chart because of the time efficiency and user satisfaction of the graph type. To represent data that changes over time, temporal data, a scatter plot is recommended. This recommendation is despite of literature showing that a line chart would work best. Shaheen et al. (2019) argue, however, that future work is needed to further deepen the results.

3.2.2 Outliers

The tool that will be built will have to deal with raw production data, containing much unfiltered data. Before this data can be visualized and analyzed, it is important to filter out false measurements (e.g. too low/large cycle times) as otherwise false conclusions can be drawn. These too low/large measurements are called outliers and must be deleted beforehand. In literature, many different methods exist to detect outliers in a dataset. From methods that rely on simple calculations to far more comprehensive methods relying on difficult calculations. Here, two methods are discussed to detect outliers: one using the Inter Quartile Range (IQR), the other one using the standard deviation. Besides, three methods to deal with outliers are discussed.

Outliers detection

A basic method to detect outliers is with the help of the Inter Quartile Range (IQR) and is called the "1.5 x IQR-rule" (Ghasemi & Zahediasl, 2012; Meijer, 2018). The IQR contains the middle 50% of the observations of a dataset and takes the difference between the third (Q_3) and the first quartile (Q_1) of a dataset. Observations outside the range $(Q_1 - 1.5 \times IQR, Q_3 + 1.5 \times IQR)$ are considered as outliers (Ghasemi & Zahediasl, 2012; Kwak & Kim, 2017; Meijer, 2018). Observations outside the range, however, do not have to be "real" outliers in the sense of measuring faults or false observations. The relatively small and large observations could be completely normal for a certain population. The "1.5 x IQR-rule" only helps to determine these potential outliers. To avoid marking observations as outliers too easily, the "3 x IQR-rule" is often used instead of 1.5 x IQR. Observations smaller or larger than 3 x IQR are considered to be "extreme outliers" (Ghasemi & Zahediasl, 2012).

An alternative method is to use the so-called "3 x s-rule" (Meijer, 2018). Here, potential outliers are the observations three standard deviations (s) away from the mean ($\overline{x}$) and thus outside the range $(\overline{x} - 3s,\ \overline{x} + 3s)$. For symmetric, mound-shaped distributions, only 0.3% of the observations will be outside this range (by the empirical rule; Meijer, 2018). Criticisms say that this method is inadequate for determining outliers, as the mean and the standard deviation are influenced by outliers in a dataset (Kwak & Kim, 2017).

Dealing with outliers

After the outliers are detected using one of the rules identified above, it must be determined how the outliers are dealt with. In general, there are three ways to handle outliers (Kwak & Kim, 2017):

- **Trimming.** This method trims the dataset by excluding the outliers. As a consequence, the variance of the dataset decreases. As a consequence, a distorted picture is created because by removing the outliers, the estimators are under- or overestimated. This method is not the best manner to deal with outliers, as the outliers are also observations (Kwak & Kim, 2017). Only if it is sure that the outlier is a consequence of an error (i.e., mismeasurement), the outlier can be deleted and ignored safely (Meijer, 2018).
- **Winsorization.** This method entails modifying either (a) the weights of the outliers or (b) the outliers themselves (Kwak & Kim, 2017). By changing the weights of the outliers, the effect of the outliers on the estimators is decreased. The outliers themselves can be replaced by some other values of the dataset, for example the minimum value without outliers. This way, the outliers are not completely removed but smoothed with the rest of the dataset.
- **Robust estimation**. Robust estimation entails replacing the value of the outlier with estimators, which are consistent and less sensitive for outliers. This method is only possible if the distribution of the dataset is known, as otherwise it would not be possible to make correct estimators. Methodological difficulties makes this method difficult to apply (Kwak & Kim, 2017).

The options trimming and winsorization will be used and built-in in the tool. Robust estimation can only be applied if the distribution of the dataset is known, which is currently not known. The choice for trimming or winsorization will be made by the user of the tool. Winsorization, however, seems the best method as it prevents creating a distorted picture.

3.3 Cycle time tool

The cycle time tool that has been built consists of nine sheets. It is chosen to use multiple sheets to (a) (separate and therefore) speed up calculations and (b) give different insights at different sheets. In the first sheet, raw production data including production times of all lines can be pasted in the format as extracted from the ERP system. On the second sheet, the user can sort the data of the first sheet so it can be read correctly by the tool. Via a drop-down menu, the assembly line for which the cycle times will be calculated can be chosen. By pressing a button, all information of the selected line is copied to this sheet. Via a second button, the data is cleaned (suing a self-constructed code, see Appendix C) in order to be sure only good data (i.e., no order that are finished twice, etc.) is used in the calculations. On the third sheet, all the data of an order can be aggregated into one single row.

The fourth sheet is one of the main sheets of the tool and contains a dashboard, which is depicted in Figure 3-1. In this sheet, the cycle times of orders of a (semi-finished) product of the selected line can be extracted, calculated and visualized. More specifically, three cycle times measures per order are calculated: (1) cycle time per order, (2) cycle time per product and (3) cycle time per product multiplied with the number of workers. This last measure makes a comparison between different orders (and products) possible, as differences in batch sizes and number of workers are eliminated. The calculation of cycle times is automatically initiated by selecting a semi-finished product in the dashboard. Besides the calculations, all measures and graphs of the dashboard are updated when selecting a product. The graphs are based on the literature of visualizing data (see Section 3.2.1). Lastly, the user can filter out outliers by pressing the button and selecting the right method to detect and handle outliers. The user can select all methods to detect and handle outliers identified in Section 3.2.2, including the use of custom borders. The cycle time per product multiplied with the number of workers is used for the determination of outliers.

On the next sheet, the user is able to calculate the cycle times of all semi-finished products of a line at once. The dashboard of this sheet exemplarily for line 5 can be seen in Figure 3-3, (graphs based on Section 3.2.1). The aim of this sheet is to provide an overview of all semi-finished products to perform analysis.

The dashboard of this screen is focused on the trends visible in the data (e.g., frequency with which a certain range occurs, the mapped cycle times, etc.). In the dashboard, the correct method to detect and handle outliers can be chosen for both (1) within each and (2) over all semi-finished products.

The sixth sheet is another important sheet with a dashboard depicted in Figure 3-2. This sheet contains an overview of the cycle times per category. To perform analysis on the cycle times of equal products, only the semi-finished products of line 5 are categorized. The sixth sheet is able to aggregate all semi-finished products within a category and calculate the measures. The graphs on the dashboard are based on the information of Section 3.2.1 and are visualizing the trends in the data as in the previous sheet.

The last three sheets are used internally by the tool for either (1) input for the drop-down menus, (2) to aggregate the order number to the correct semi-finished product and (3) loop over all (unique) semi-finished product. A more elaborate explanation of the tool can be read in Appendix C, in which a user manual is provided. Each sheet and the code that works in the background is explained there. Besides, a screenshot of each of the nine sheets is depicted here.

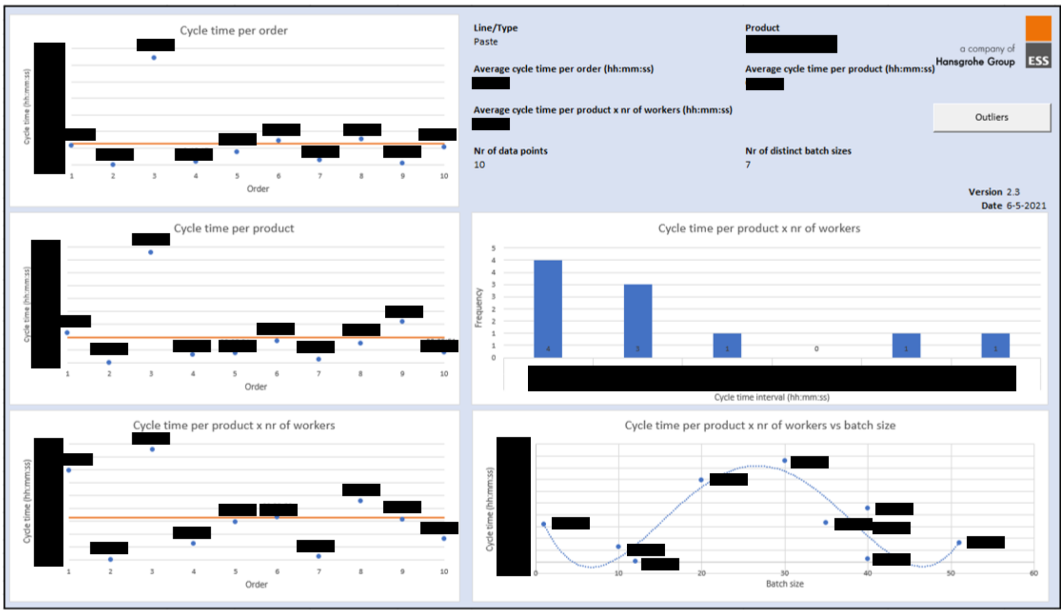


Figure 3-1: Dashboard of the cycle time tool containing information about the cycle times of a selected semi-finished product (outliers detected using "1,5 x IQR" and handled using "winsorization"). Some results are anonymized because of confidentiality.

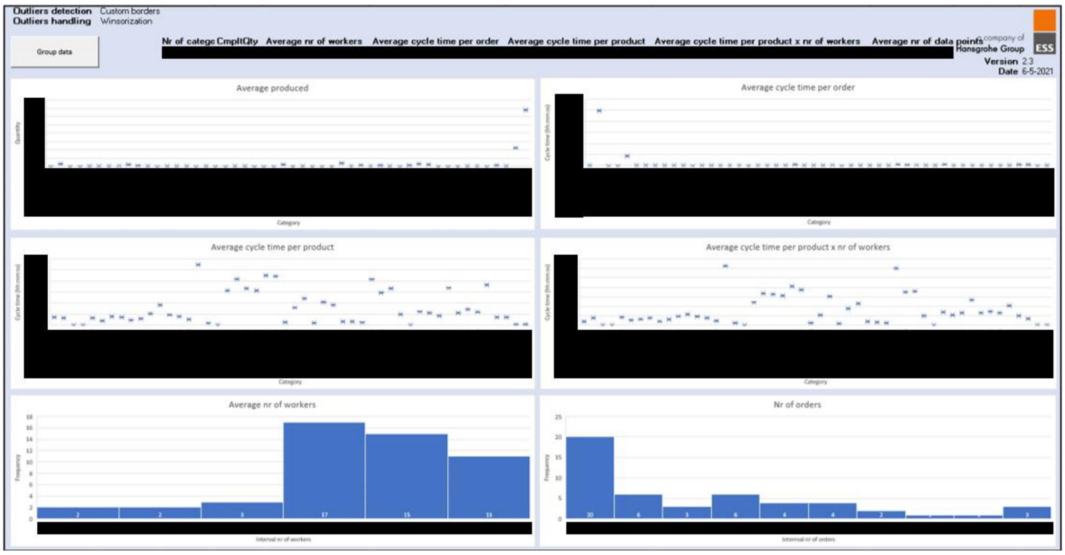


Figure 3-2: Dashboard of the cycle time tool containing information about the cycle times of all semi-finished products of a category (only line 5, outliers detected using "1,5 x IQR" and handled using "winsorization"). Some results are anonymized because of confidentiality.

Figure 3-3: Dashboard of the cycle time tool containing information about the cycle times of all semi-finished products of a type (line 5) or line (outliers detected using "1,5 x IQR" and handled using "winsorization"). Some results are anonymized because of confidentiality.

3.4 Results

The tool is able to calculate many different measures, both product-specific, per order type (laser, paste, or assembly) or over all orders produced on the line. As it would take too much space to place all results here, only the aggregated results of all orders of the container-series line are shown and highlighted. The results of the order types laser, paste and assembly can be seen in Appendix C.11. Figures 3-4 till 3-8 and Table 5 contains the most important results of the cycles times of all orders produced on line 5.

The averages are calculated by using all data available of the cycle times. As the tablet system was fully functioning since 01-01-2020, this is the earliest date of which there is data. The averages per (semi-finished) product are visualized in the figures and calculated by using the individual measures of the orders of the product. Per order, only a round number of workers can work on the order. By taking the average number of workers per product, the average per product is calculated and can result in a half worker.

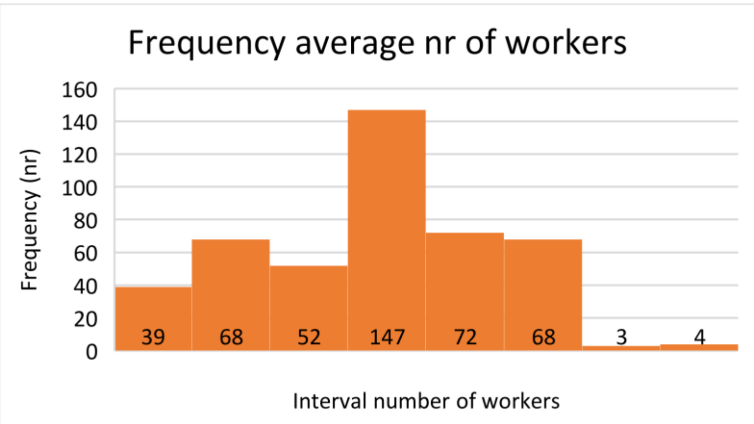


Figure 3-4: Frequency of the average number of workers that have helped producing an order in an interval of 0.5 (over all semi-finished products of line 5). Chart axis removed due to confidentiality.

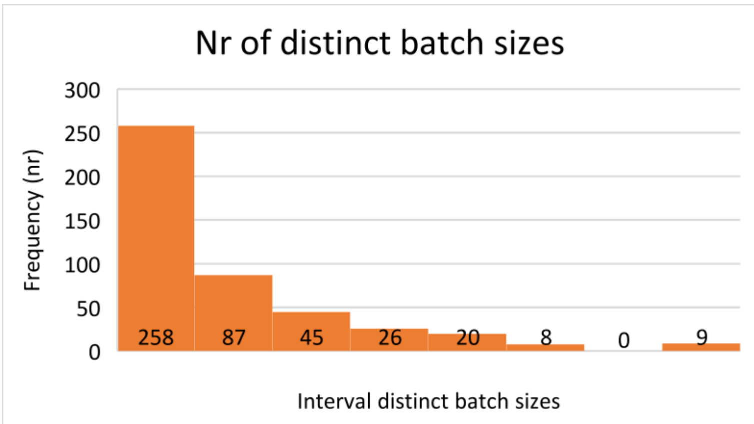


Figure 3-5: Frequency of the number of distinct batch sizes per semi-finished product (over all semi-finished products of line 5). Chart axis removed due to confidentiality.

Figure 3-6: Overview of the frequency of the number of orders within a product. Chart axis removed due to confidentiality.

Table 5: Overview of the measures calculated on the dashboard (over all semi-finished products of line 5). Data censored due to confidentiality.

Nr of products	Average quantity of products	Average nr of workers	Average cycle time per product *(hh:mm:ss)*
[redacted]	[redacted]	[redacted]	[redacted]

Average cycle time per product x nr of workers *(hh:mm:ss)*	Average nr distinct batch sizes	Average nr of data points
[redacted]	[redacted]	[redacted]

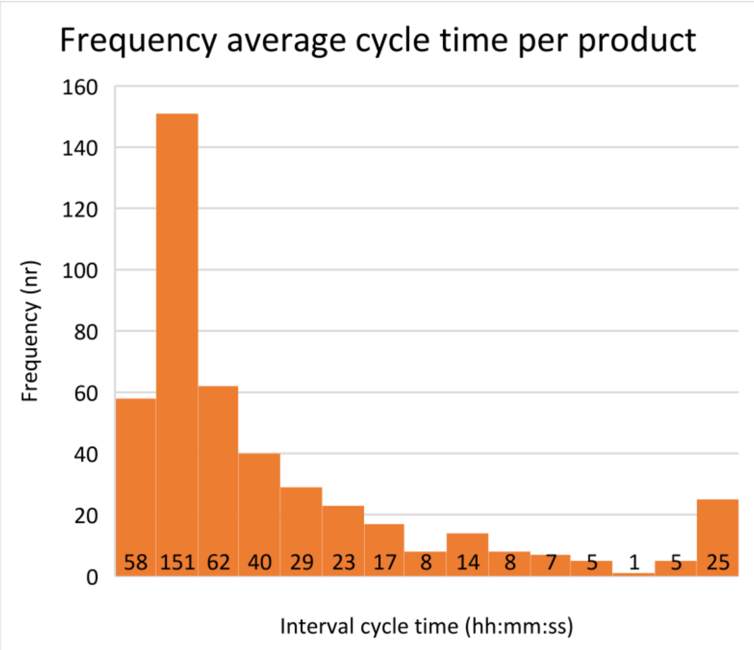


Figure 3-7: Frequency of the cycle times per semi-finished products per interval (over all semi-finished products of line 5). Chart axis with cycle times removed due to confidentiality.

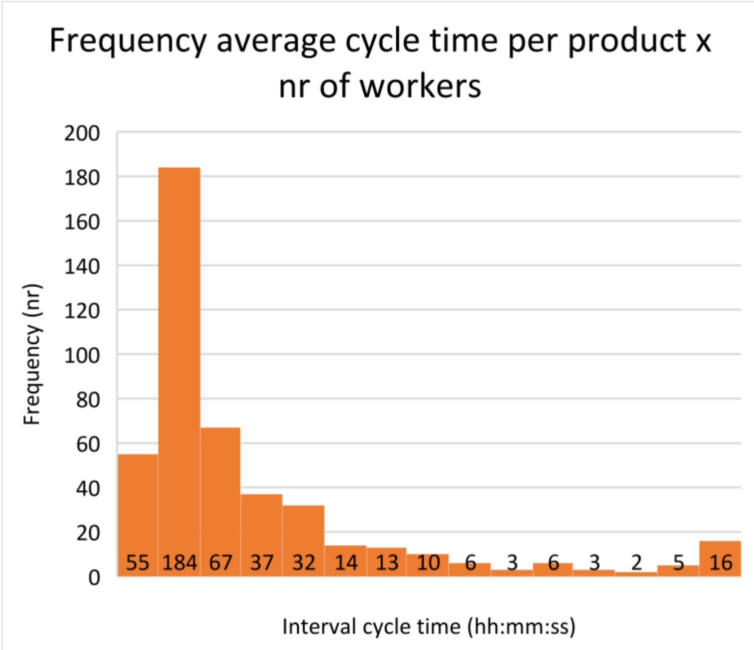


Figure 3-8: Frequency of the cycle times per semi-finished products multiplied with the number of workers per interval (over all semi-finished products of line 5). Chart axis with cycle times removed due to confidentiality.

3.5 Analysis of results

Analyzing the results of the cycle time tool, the following conclusions can be drawn:

- **The data is in general complete**. The raw production data sometimes contains an order that is started or paused multiple times. The cycle time tool is able to find such orders and can take the correct follow-up actions (e.g., delete only one row or the rows of a complete order). In case of line 5, only seventeen of almost six thousand rows are deleted. As there are little rows deleted by the tool, the completeness of the data is in general large.
- **Some orders have very small or large cycle time**. In the data, there are a lot of orders that have a very low or very large cycle time. For some orders, the cycle times are very low. The reason for this is that the worker on the line probably forgets to start an order in time. As this is not seen immediately, some orders have a very low cycle time. On the other hand, there are also orders that have a way too high cycle time. Investigating these cases show that the workers have forgotten to pause the order in the break, when another order is started because of an issue or when the day ended. Consequently, these cycle times are unrealistically high. To prevent this, ESS can either give additional trainings or change aspects of the current tablet system (see recommendations in Chapter 7).

- **Some outliers are not removed**. As the number of orders per product is low and the spread of the cycle times (per product multiplied with the number of workers) is relatively large, the statistical upper border (UB) used in the detection of the outliers is very high. Consequently, many orders with a large cycle time are not detected as outliers. Simultaneously with the high upper border, the calculated statistical lower border (LB) is often negative due to cycle times of close to zero. As negative times are not possible, the lower border is set equal to zero. The result of this is that orders with an unrealistically low cycle time are not detected as outliers. To counteract the too LB border and too high UB, a feature is added to the tool to set custom borders. With the setting of the custom borders, practical considerations (e.g., only cycle times that are practically possible) can be considered when setting the border. The statical methods, however, are still usable as these filter and handle outliers only on statical reasons and are, therefore, not biased by the user. It appeared that a combination of custom and statical borders (custom LB and statistical UB) worked well and give reasonable results.
- **Cycle times of the laser orders are not reliable**. Investigating the cycle times of the laser orders, it can be seen that there are a lot of orders with a very low cycle time. For example, the cycle time of an order containing 109 items takes nine seconds, while in reality it takes already about nine second to laser one item. Besides, the time it takes to walk and transport all items that must be lasered is also not considered in this cycle time. The poor data is a consequence of not recording the start and finish time of the order with discipline in the correct way. As this is only discovered when the order is booked finish, the person starts and immediately finishes the order on the tablet instead of only finishing the order. This way, an unrepresentative cycle time is stored in the system. Therefore, cycle times of laser orders can better be assumed to be constant, including a factor for walking time.

Based on the analysis of the data, I conclude that the overall quality and completeness of the data is good enough to use the tool and the data both internally and in the rest of this research. In the next chapter, the cycle times as calculated by the tool are used in the determination process of more optimal batch sizes.

3.6 Conclusion

This chapter described the tool that has been made to give insight in the current cycle times. The eventually built tool consists of nine sheets, each depicting different measurers and having its own function. Analyzing the results of the tool, the following conclusions have been drawn: the data is in general complete, some orders have very small or large cycle time, some outliers are not removed and cycle times of the laser orders are not reliable. Moreover, it has been argued that overall quality and completeness of the data is good enough to use the tool and the data both internally and in the rest of this research.

4. Batch size determination

This chapter describes the process of determining batch sizes that reduce cycle times. Section 4.1 explains the global approach that is used. Section 4.2 describes the literature studies performed to gather knowledge for the approach. Based on the literature studies, the method is defined more properly which can be read in Section 4.3. Section 4.4 provides the actual determination process of the batch sizes. A sensitivity analysis is performed on the determined batch sizes, which is provided in Section 4.5. Lastly, Section 4.6 provides a summary of the contributions of this chapter.

4.1 Approach

For the determination of batch sizes, a literature study will be performed to get an overview of the existing methods to determine batch sizes that reduce cycle times. From the methods identified, one method will be selected that is most suitable for the use at ESS. Data for the selected method will be gathered and the batch sizes that reduce cycle times will be calculated. Because a lot of other stations and parties are affected by the choice of the batch size, these must also be considered in the recommended batch sizes. These factors are compared with the determined batch size from the method and conclusions are drawn regarding the batch sizes that are both good for the cycle times (reduces the cycle times) and feasible for the rest of the process. To validate the result, a sensitivity analysis will be performed.

4.2 Literature

This section provides the knowledge that is gathered for the determination of batch sizes that reduce cycle times. It starts with the identification of existing methods in literature to determine batch sizes. Next, literature on the identification of factors considered in the determination process are provided in Section 4.2.2. Section 4.2.3 provides information about the relation between two variables. Lastly, Section 4.2.4 describes the literature study performed to gather knowledge about sensitivity analyses.

4.2.1 Batch size determination method

This section provides information about two existing methods in literature to determine batch sizes, named Economic Production Quantity (EPQ) and optimal (serial) batches with multiple products.

Economic Production Quantity

The Economic Production Quantity (EPQ) is a method used by many authors in literature to calculate batch sizes (Abboud et al., 2000; Cárdenas-Barrón, 2009; Chen & Chiu, 2011; Chiu et al., 2008; Farsijani et al., 2012; Lee & Fu, 2013; Pasandideh et al., 2010). In this model, a trade-off is made between production setup/ordering and inventory cost. In case of the EPQ, the total cost related to a certain batch size is the sum of the production setup and inventory cost (Chopra & Meindl, 2016).

The optimal batch size is the batch size that minimizes the average cost per time unit (Chiu et al., 2010). The formula for the optimal batch size can be derived from the total costs formula by taking the first derivative with respect to Q^P, set this equal to zero and isolate Q^P (Chopra & Meindl, 2016). One obtains the following formula:

$$Q^P = \sqrt{\frac{2DS}{\left(1-\frac{D}{P}\right)hC}}$$

In which:

D	=	Annual demand of the product	S	=	Cost incurred per setup
P	=	Production rate	h	=	Holding cost per year as fraction of C
Q^P	=	Production lot size	C	=	Unit cost incurred per product

The EPQ models are flexible and can be adapted to, for example, take quality problems or rework into account (Chiu et al., 2010; Liao & Sheu, 2011). This method is, however, not suitable to use in this thesis, as cost minimization is not the key objective for ESS. Instead, the key objective is to increase the production capacity or productivity per worker to be able to produce more items in the same amount of time.

Optimal (serial) batches with multiple products

A method that is minimizing cycle time is described by Hopp and Spearman (2008). They state that cycle time increases proportional with larger batch sizes in stations with large changeovers or batch operations (law of "Process Batching"). Moreover, they state in the same law that there is a batch size that minimizes the cycle time at a station. This batch size can be calculated using a mathematical model: "optimal (serial) batches with multiple products".

Hopp and Spearman (2008) argue that a station (e.g., an assembly line) can be modelled as a queuing system. Because of that, a formula to estimate the cycle time of a queue can be used coming from this queuing system. With the help of this formula, it is argued that the batch sizes that minimize the cycle time can be found by minimizing the run length of the system. By solving this optimization problem (either exact or by approximation), a (minimized) run length can be found. With this run length, including setup and process time, a set of lot sizes can be determined that minimize the cycle time at a station.

The law and method described by Hopp and Spearman (2008) can, however, also not be used in this thesis. This is because in the law and method, the time in queue is one of the major components of the cycle time and is minimized in the model proposed. As this is not important in the process of the container-series line, this method cannot be used to calculate batch sizes.

Intermediate conclusion

In literature, no suited method has been found to calculate the batch sizes that reduce the cycle times. The EPQ formulas cannot be used as these formulas focus on cost minimization, which is not the main focus. The method proposed by Hopp and Spearman (2008) seems to be a good alternative but can also not be used as queue time is a main component in this method and not important in the process of the container-series line. Besides, the methods mentioned do not consider other processes in the production environment, for example sales or purchase processes. The other processes in the production environment are heavily influenced by the batch sizes used and must, therefore, also be considered in the calculation of the batch sizes. As the methods identified in literature cannot be used, an own method has to be formulated (see Section 4.3). The rest of this section describes the knowledge that has been gathered for this new method.

4.2.2 Factor identification

This section provides the literature for the identification of factors that will be considered in the determination of optimal batch sizes. The first section identifies factors influencing batch sizes considering only a single and isolated station. Next, two systematic methods are described which are used in the determination of factors considering the total production environment.

Factors influencing batch sizes single station

To identify factors that must be considered in the determination of batch sizes that reduce cycle times, more knowledge has to be gathered first about the factors that influence the calculation of batch sizes only considering a single station. A single station means that only the characteristics of a single station are considered and no other stations (e.g., by which it is fed or for which it provides output) are taken into account. By investigating these factors only for a single station, relevant factors can be identified which may be used in the determination of optimal batch sizes.

The most-frequently mentioned factors I identified in the literature, most of them are also part of the EPQ formulas, are (Abboud et al., 2000; Banerjee, 1992; Cárdenas-Barrón, 2009; Chen & Chiu, 2011; Chiu et al., 2008; Dave et al., 1996; Farsijani et al., 2012; Lee & Fu, 2013; Pasandideh et al., 2010; Sarker et al., 2008; Sarker & Newton, 2002):

- **Demand** for a certain product per unit of time. This factor is important for the calculation of the batch sizes, as it determines (1) the number of orders for components, (2) the number of batches per year and, with that, the number of times a setup/order is necessary and (3) the inventory level of both the components and finished goods. More specifically, this factor determines how fast the inventory of finished products decreases during a period in which there is no production/assembly (Sarker et al., 2008). When there is a high demand, the inventory will decrease faster and higher inventories or larger batch sizes are needed.
- **Production rate**. The production rate influences the calculation and is often assumed to be greater than the demand rate (Abboud et al., 2000; Cárdenas-Barrón, 2009; Chen & Chiu, 2011; Chiu et al., 2008). The production rate determines how fast the inventory increases during the time items are produced. When the production rate is high, the inventory will increase fast after production is initiated and smaller batch sizes can be used.
- **Setup or ordering cost**. The setup or ordering costs of a batch also influences the batch sizes. The setup costs are the costs incurred when setting up the production for a batch, which can include multiple costs (e.g., transportation, machine). The ordering costs are the cost incurred when ordering components for the produced product. This ordering cost can consist of one fixed cost or of a fixed and variable part. By having relatively high setup/ordering costs, it is economically better to have few large batch sizes than multiple smaller batch sizes (Sarker & Newton, 2002).
- **Holding/inventory**. The inventory cost are the cost incurred when a product is produced and will be placed on stock before it will be sold to a customer. It is one of the main aims of the EPQ to reduce the inventory holding cost to a minimum level (Cárdenas-Barrón, 2009). It is often calculated as the holding cost per year per product multiplied with the average inventory of a year (Sarker et al., 2008). The holding cost per year per product is most often expressed as fraction of production cost per year (Pasandideh et al., 2010). When a high holding cost is incurred, it is better to produce more smaller batches to keep the inventory as low as possible. Besides, limited space may be available in the warehouse to store the finished products, which means that the calculated batch sizes may not be feasible in real life.

Theory Of Constraints

Theory Of Constraints (TOC) is a methodology emerged in the 1980s that can be used to systematically manage and improve processes (Miguel et al., 2010; Watson et al., 2007). TOC is based on four main principles (Miguel et al., 2010): (1) any company strives for profit and if a company does not yield profit, this is due to constraints, (2) there exists a constraint in every company, (3) a constraint is either physical or political and (4) the maximum performance of a system is reached by systemic thinking.

TOC "emphasizes the cross-functional and interdependent nature of organizational processes by viewing an organization as a chain (or a network of chains) of interdependent functions" (Gupta & Boyd, 2008, p. 993). The theories and knowledge used in the TOC are no new methods but based on theories of other areas. The strength of TOC is that it combines these methods in a systematic way (Miguel et al., 2010).

TOC can be used across a wide range of different areas, for example in logistics/production, performance measures, and problem solving/thinking process (Miguel et al., 2010; Watson et al., 2007). In production processes, TOC is used to balance the flow of products throughout the whole system (Miguel et al., 2010). TOC assumes that different resources/stations have different capacities and instead of the capacities, the product flow through the system must be balanced.

Value Stream Mapping

Value Stream Mapping (VSM) is a lean method that helps identifying waste by mapping the complete production process: from raw material to a finished product (Batra et al., 2016; Braglia et al., 2006). A value stream "consists of all the materials and information required in the manufacturing of a particular product and how they flow through the manufacturing system" (Chen et al., 2010, p. 1072). VSM has been used as a tool to implement lean in a production process.

A VSM distinguishes between two types of activities: value-added activities and non-value-added activities, the latter ones also called waste. A VSM visualizes both material and information flows from one station to another (Braglia et al., 2006). Moreover, information like (station) cycle time, setup time, Work-In Progress (WIP) inventory, etc. are depicted for each workstation (Batra et al., 2016).

In a VSM, two mechanisms between parties are identified: a push and pull mechanism. A push mechanism "pushes" its output to the next station: components/products are passed on to the next station whether or not these are needed at the next station (Puchkova et al., 2016). The goods flow of a pull mechanism, on the other hand, is based on the demand of the next station: components/ products are only passed on to the next station when the next station gives a sign (or other Kanban visual) that new components/products are needed (Puchkova et al., 2016).

According to Braglia et al. (2006), VSM has several advantages. The main advantage of a VSM is that it maps the (internal) manufacturing process in relation with the supply chain it is located in. Moreover, the information flows are shown aside the material flows unlike comparable mapping methods. VSM, however, also has some drawbacks and limitations (Braglia et al., 2006; Batra et al., 2016). First, mapping a complete process and measuring all the cycle times is time-consuming. Besides, a VSM is not able to map complex production systems in which the production path is not fixed but dynamic.

4.2.3 Relation of variables

According to Gogtay and Thatte (2017), correlation is "a term used to denote the association or relationship between two (or more) quantitative variables". It measures if and how strong a (linear) relation exists between two variables (Taylor, 1990). Correlation is usually investigated by mapping the variables in a scatterplot and drawing a trendline through the datapoints. The correlation coefficient is a measure that expresses the amount of correlation and is a value between minus and plus one. The sign of the correlation coefficient represents the direction of the correlation (+ for positive relation and - for negative relation), while the size of the correlation coefficient indicates the strength of the correlation (Gogtay & Thatte, 2017; Taylor, 1990). An overview of the interpretation of the correlation coefficient can be seen in Table 6.

To calculate the correlation coefficient, Pearson's correlation coefficient is often used (Gogtay & Thatte, 2017; Taylor, 1990). The correlation coefficient only indicates that a linear relation exists between two variables. The exact linear equation, however, is not indicated. When one wants to know the exact relation, (linear) regression can be used (Asuero et al., 2006; Gogtay & Thatte, 2017; Taylor, 1990). In linear regression, a mathematical model of the form $Y = b_0 + b_1x_1 + \epsilon$ that best fits the data is constructed by minimizing the sum of the squared errors.

Table 6: Interpretation of correlation coefficient.

Value	Interpretation
0	no correlation
0.01 to 0.35	low/weak correlation
0.36 to 0.67	moderate correlation
0.67 to 0.89	high/strong correlation
0.89 to 0.99	very high correlation
1	perfect (linear) correlation

To evaluate the performance of a regression model, the r squared is often used (Asuero et al., 2006; Taylor, 1990). The r squared, or coefficient of determination, is the proportion of the variation in the dependent variable that can be explained by a variation in the dependent variable (Taylor, 1990). How closer the r squared is to 1, the more variation of the dependent variable is explained by the variation in the independent variable. The fit of a model is good when the r squared is equal or close to one.

When the variables do not seem to be linearly related, a nonlinear relation may still exist. In these cases, the correlation coefficient can be calculated using Spearman's rank correlation coefficient and Kendall's rank correlation coefficient (Wang et al., 2015). To determine the equation of the curve through the data points, polynomial or nonlinear regression can be used (Motulsky & Ransnas, 1987). The problem with nonlinear regression, however, is that it cannot be solved easily.

A final note on this subject is about the influence of the sample size and outliers on the coefficient of variation. A small sample size can result in a situation in which it looks like there is a linear relation between two variables (according to the statistical measures) but in reality there is no linear relation (Gogtay & Thatte, 2017). Besides, outliers can result in a completely other value of the coefficient of variation and in a wrong conclusion (Asuero et al., 2006). Therefore, outliers must be detected and handled (see Section 3.2.2) carefully before calculating the correlation coefficient.

4.2.4 Sensitivity analysis

A sensitivity analysis is “the study of how the uncertainty in the output of a model numerically or otherwise) can be apportioned to different sources of uncertainty in the model input” (Saltelli, 2002, p. 579). In other words, it is investigated how the found solution depends on the (input) data or the assumptions and simplifications. By providing information on the changes of the output by changes of the input, extra quality is added to a model (Castillo et al., 2008).

Sensitivity analysis can provide valuable information about the sensitivity of a model. In case the model is insensitive to changes in the input data, a suboptimal solution can be better than the optimal solution in which significantly more money or time need to be spent (Pannell, 1997).

Many methods exist in literature to perform a sensitivity analysis. According to Frey and Patil (2002), these method can be divided in three main categories:

1. **Mathematical methods**. Sensitivity of a model is investigated by the range of (possible) input variables. Frequently, a few values of input variables are assessed that represent all the (in theory) possible values.
2. **Statistical methods**. By doing simulations with inputs modelled as probability distributions, the input can be compared with the outcome to assess the sensitivity. These kinds of methods allow the user to assess the effect of the interaction of (different) input variables.
3. **Graphical methods**. Sensitivity of a model is assessed by the use of graphical elements like graphs and charts. By changing the output of (different) combinations of input variables, the sensitivity of the model can be determined visually. Generally, graphical methods are used to support mathematical and statistical methods.

4.3 Revised approach

Because no method to calculate batch sizes from literature can be used directly, an own approach has to be formulated. To determine the batch sizes that reduce the cycle time, a data perspective will be used. The tool that is made to give insight in the current cycle times will be used to gather data to investigate the relation between batch sizes and cycle times. By mapping these measures of historical orders, it will be investigated (if and) which patterns can be discovered between the cycle time and batch size used. By using statistical measures, the relationship will be investigated, and a conclusion will be drawn about the optimal batch sizes for cycle time reduction.

The batch size determined from the data will be compared with batch sizes optimal for certain factors. Each of the factors will be measured separately and the relations with batch sizes of the container-series line will be investigated more thoroughly. Afterwards, the measured factors will be combined in order to come to a conclusion about the batch sizes. Consequently, batch sizes will be proposed that are both beneficial for the station (i.e., reduce the cycle time) and for the other parties of the production process. To validate the result and to increase the strength of the method, as sensitivity analysis will be performed on the determined batch sizes.

As this process is time-consuming and the execution time is limited, this process will be executed for only a small selection of products. The selection of products will be made carefully in cooperation with the company. Besides, data of similar products (e.g., other colors, dimensions) are aggregated in order to have more data and be able to draw a stronger conclusion about the (possible) relation.

4.3.1 Value Stream Map

Applying the VSM theory of Section 4.2.2 to the production process of ESS, a value stream map has been created and is provided in Figure 4-1. By mapping the key activities in the production process (e.g., the activities with most handling time), the factors that are affected by the choice of batch size can be identified more easily. The value stream is based on the layout and business process model of the production facility as drafted in Section 2.1.

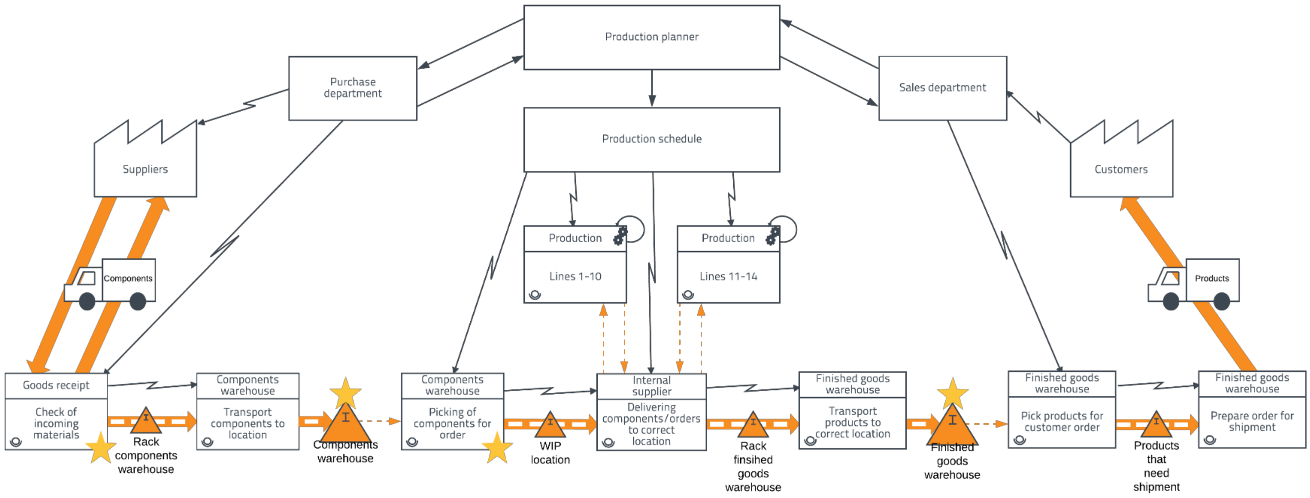


Figure 4-1: Value Stream Map (VSM) of the production process of ESS, with possible limiting factors (marked with a star) for batch sizes.

A note on this VSM is that it does not contain information about a single station/party like cycle time or capacity. The map is only made to identify (possible) limiting factors for batch sizes. Consequently, the VSM in Figure 4-1 is no formal VSM as a formal VSM includes these measures.

Analyzing the VSM, factors are identified that are (possible) limiting factors. These (possible) limiting factors are marked with a star in Figure 4-1. First, the process of the goods receipt could be limiting, as more components can be needed at once and this can be a problem. Second, the components warehouse has a limited capacity of components. Moreover, the batch size cannot be greater than the available stock of components. Next, the pick process could be limiting, as more components will cost more time to pick which cannot be spent on pick actions for other lines. Lastly, the finished goods warehouse could be limiting in terms of capacity.

4.3.2 Final set factors

Combining the factors that are currently used in the determination of batch sizes, factors identified in interviews with stakeholders and factors identified by applying TOC and VSM to the production process of ESS, many possible factors have been identified. Due to the limited time available, only the most important factors are considered. The most important factors are the factors that are influenced heavily by the choice for a certain batch size and are:

- **Goods receipt**;
- **Purchase quantities**;
- **Components warehouse**;
- **Pick process**;
- **Finished goods warehouse**;
- **Sales**.

4.3.3 Measuring the station cycle time and factors

This section elaborates more on which information is gathered and how this will be gathered for the determination of the station cycle time and for each factor (as identified in the previous section). Moreover, some remarks and focus points for the station cycle time and per factor are provided.

Station cycle time

The batch size that reduces the cycle time for the products is determined by mapping the cycle times against the batch sizes used. Patterns and relations are investigated by using Excel (among others plotting and trendlines) and statistical measures. Products which are approximately the same (i.e., same product, different color) are aggregated in order to have more data points.

A note must be made about the different order types a product consists of. As explained in Section 2.2, a final product requires one, two or three types of order (laser, paste and assembly). Per product, the different order types that are needed to produce a product are investigated separately and combined in one advice for the (region of) batch size(s). The relation between the cycle time and batch size for the laser type, however, is not investigated. The reason for this is that the quality of data of the laser orders is very poor (see Section 3.5). Instead of the relation between the batch size and cycle time, a general rule is investigated for the laser order type.

Goods receipt

The time it takes to perform all processes at the goods receipt (see Section 2.3) will be measured two mornings using a stopwatch. Two types of processes will be investigated separately: (1) unloading a truck and (2) performing the quantity and quality checks and book the components in the system. The time these processes takes will be measured manually, the quantities handled during these processes will be counted and noted.

It is not possible to measure this time only for the components that are used for certain products of the container-series line as the frequency is relatively low and, thus, too less data is gathered. Therefore, a general relation between the quantity of incoming components and the time it takes to do all processes at the goods receipt is investigated.

Purchase quantity

This factor investigates the purchase quantities of the components used in the products. More specifically, the fixed purchase quantity in which the components can be bought is investigated. Besides, the minimum or maximum purchase quantities are investigated. The purchase quantity is only investigated for components that are not bulk components or (used in the) accessories (assembled on lines 11-14). The reason for this is that these components are currently purchased in bulk and, therefore, the purchase quantity of these components are not considered to be a (possible) bottleneck for the batch sizes. The information regarding the purchase quantity is gathered by performing interviews with the purchase manager. Besides, data of the components is requested from the purchase manager.

Components warehouse

Ideally, the historical stock level is investigated to determine the maximum and average stock level of a component, which can be used to draw conclusions about possible batch sizes. The historical stock level, however, is not available. In cooperation with the company, it is decided to use the current stock level (of 15-06-2021) as a reflection of the normal stock level of the components. This current stock level is used to make statements about batch sizes. Based on these levels, a conclusion can be drawn about the batch sizes that are possible. A factor making this more difficult is that some components are used as input for different products. Therefore, the complete stock cannot be assigned to only one product. This must be considered when drawing a conclusion about the batch sizes that are possible.

In addition to the stock level, the capacity for a certain component in the components warehouse is investigated. It can be the case that the current stock is not adequate for the batch size determined and the advice is to increase the stock level of the components. There must be, however, enough space in the components warehouse to store the components. Therefore, this number is balanced with the advice to determine if the proposed stock is possible.

Just as the purchasing quantity, this factor is only investigated for components that are not bulk components or (used in) accessories. The information of the components that are investigated is gathered from the ERP system and by performing interviews with the involved parties.

Pick process

The time it takes to finish a pick order is measured using a stopwatch. More specifically, the measurement starts when a picker starts the order on the scanner and ends when the order is delivered at the WIP location and the pick order is booked as finished on the scanner. As the time it takes to finish a pick order is not recorded in the ERP system, this must be measured manually. The number of products (for which the pick order is) is determined by the production schedule. The time it takes to finish a pick order is mapped against the size of the production order for which the pick order is. From this map, a conclusion can be drawn regarding this factor. To increase the availability of data, a general relation between quantity and the time is investigated (just as the goods receipt).

Finished goods warehouse

First, the total reserved places for the products must be determined to get an idea about the maximum batch size possible. Besides, the total capacity and utilization rate of the finished goods warehouse must be determined as it could be the case that the reserved places are inadequate and the advice will be to still use larger batches. Moreover, other information like quantities that are optimal for the finished goods warehouse are gathered by performing an interview with the head of this warehouse. The rest of the information is gathered from the ERP system

Sales

The last factor that is considered in the determination of batch sizes is the sales. Some products are only sold in fixed quantities and, therefore, it is logical to make batches equal to (or slightly larger than) this fixed sell quantity. The information regarding the fixed sell quantity is gathered via the ERP system and performing interviews with the sales department. Besides the fixed sell quantity, information around demand is gathered. Data regarding historical demand can be gathered via the ERP system. Forecasted demand is gathered via the purchasing department. Other sales factors are gathered by performing interviews with sales employees and export managers (of France and Germany). Based on the fixed sell quantity and demand (both historical and forecasted) a conclusion can be drawn regarding this last factor.

4.3.4 Product mix

Based on the available data regarding the batch sizes and cycle times, the production schedule, the product groups (see Section 1.3.4) and a discussion with the company about good, representing products (of the container-series line and of the four groups), the batch sizes of the following products will be investigated (an overview of the complete list of all orders and products can be seen in Table 23 in Appendix D, names anonymized):

- **Basic-(1 to 4)** (basic group);
- **Simple-(1 to 4)-(Small, Medium or Large)** (simple group);
- **Medium-(1 to 4)-(Small, Medium or Large)** (medium group);
- **Difficult-(1 to 4)-(Small, Medium or Large)** (difficult group).

4.4 Batch size determination

This section shows the determination of the batch sizes per factor. As a general relation is investigated for both the process of the goods receipt and the picking of materials, these sections only contain one relation for all products. The rest of the factors are split for each of the groups identified above.

4.4.1 Station cycle time

The data of the cycle times per product multiplied with the number of workers and batch sizes are extracted from the ERP system and loaded in the cycle time tool (see Section 3.3). The cycle times per product multiplied with the number of workers (in the rest of the chapter referred as cycle time) is used to eliminate differences in number of workers and batch sizes. With the help of this tool, the cycle times and batch sizes of the products are calculated and gathered.

The outliers within the data of a (semi-finished) product are removed by using the outliers feature of the tool. It is chosen to filter out the outliers per product and not over all products of a group as certain cycle times can be perfectly fine for one semi-finished product while not normal for another product. When outliers are removed over all semi-finished products, however, these large cycle times are filtered out. Therefore, the data of each semi-finished product is calculated, gathered and filtered on outliers separately using the tool. To detect outliers, a combination of a fixed, practical border (lower bound) and variable, statical border (upper bound) is used because this combination is seen as both practically and statistically correct for the detection of outliers. The lower bound is set manually for each group (based on the data and practical insights), the upper bound is determined using the "1.5 x IQR" rule (Section 3.2.2). To keep as many possible data points as possible, the outlier handling method is set on winsorization.

At the start of each section (except the laser order), information regarding the correlation and fit of the linear regression line is give. This information is referenced to and used to analyze the relation in the scatterplots. Moreover, a note must be placed on the scatterplots that follow. In these scatterplots, the relation between the cycle time and batch size will be investigated. To ease analysis, linear regression lines and trendlines will be used. These lines, however, are not the main goal: the lines only help to visualize the pattern and relation in the data. The conclusion regarding the optimal batch sizes will be based on both the trend(lines) and the distribution of points.

Basic group – laser

To determine the batch size optimal for the laser order, first information about the laser machine and the process is gathered. According to one of the R&D employees, it takes about seven seconds to laser an item, including placing the component, actual lasering (which takes only 1.49 seconds according to specification of the laser machine) and removing the component. Moreover, the R&D employee argued that removing the foil for lasering takes two to three times the laser time.

To verify the statements of the R&D employee, the laser time has been measured manually for a laser order of the products in the basic group. Table 24 in Appendix D contains the raw data gathered during the measurements. According to the measurements, it takes on average 7.1 seconds to laser an item and 12.2 seconds to remove the foil. One item, therefore, takes about twenty seconds to be finished. Besides, the time to prepare and execute an order is measured. The preparation of an order consists of walking to the machine, arranging the pallets, placing the correct mold and choosing the correct program on the machine. The time measurement results in a preparation time of about five minutes for an order and a total time of about 39 minutes (to be precise [redacted] , hh:mm:ss) with a batch size of 200 and two workers helping. I identified the following rule for the constant of a laser order of the products representing the basic group (assuming two persons work on the order, hh:mm:ss):

$$\begin{aligned} Laser\ order &= preparations\ + (removing\ foil + laser\ item) \times nr\ of\ items \\ &= 00{:}05{:}00 + 00{:}00{:}20 \times nr\ of\ items \end{aligned}$$

Basic group – paste

Pearson / Spearman correlation coefficient: -0.178 / -0.063

R^2 Linear regression line: 0.032

Figure 4-2 shows a scatterplot of the cycle times versus batch sizes of the paste orders of the products within the basic group. The correlation coefficients are in the low category (see Table 6), meaning that there is a weak, negative correlation between the variables.

Analyzing this scatterplot, two kinds of trends can be identified: (1) a cluster of datapoints at the bottom left of the scatterplot and (2) a linear downwards trend of points from the upper left of the scatterplot to the lower right.

Applying linear regression to the data (dotted blue line), a general decrease in cycle time can be discovered. This decrease is probably a consequence of the setup time included in the cycle time: the setup time can be divided over more products when large batch sizes are used and, thus, the average setup time decreases when having larger batch sizes. It must be noted, however, that there is a poor fit between the data and the linear regression line as the R^2 is low. Besides, there seems to be some kind of fixed, frequent scheduled batch sizes, indicated by multiple dots on a vertical line (at a batch size of 50, 70 and 200).

Combining the trends as identified above, a custom trendline is drafted (dashed yellow line). This trendline shows that small orders have a relatively large cycle time, which decreases quickly when using larger batch sizes. The marginal decrease, however, becomes smaller and stagnates when using larger batch sizes. Looking at the scatterplot, I conclude that a batch size of greater than (about) 60 seems optimal as the decrease in cycle time before this point is relatively larger than the decrease after this point.

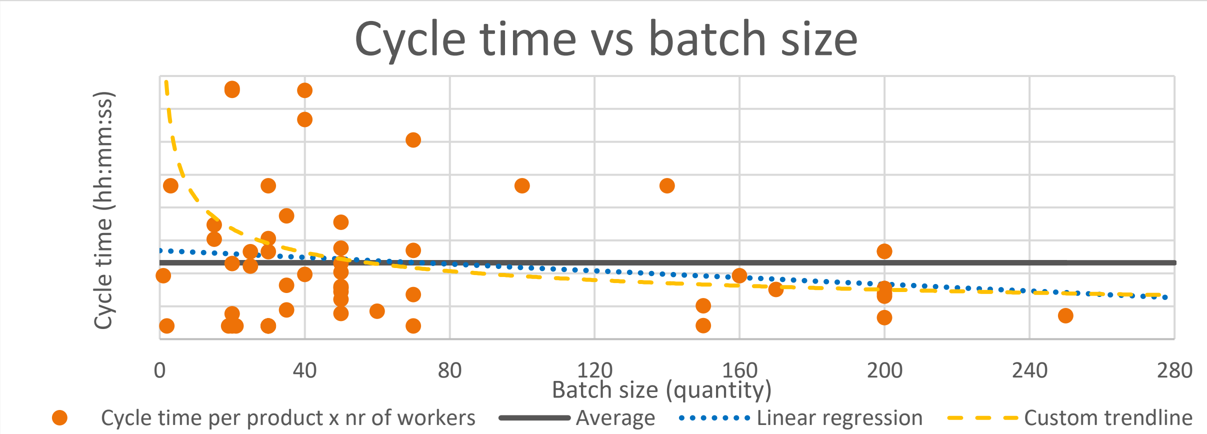


Figure 4-2: Scatterplot of the cycle time (per product x nr of workers) vs batch size for the paste orders of the product mix representing the basic group. Chart axis with cycle times removed due to confidentiality.

Basic group – assembly

Pearson / Spearman correlation coefficient: -0.192 / -0.136
R^2 Linear regression line: 0.037

The scatterplot of batch size versus cycle time is shown in Figure 4-3. According to the correlation coefficients, a weak, negative correlation exists between the two variables. A similar relation as the paste order can be seen: a lot of points at the bottom left of the scatterplot and an overall decreasing trend when batch sizes increase. The linear regression line (dotted blue line) confirms this decreasing trend (although the model fit is poor). This decrease is again probably due to the division of setup time over a larger batch. A difference in the trend with the paste order, however, is that there seems to be an increase in the cycle times after (about) 150. This increase seems to increase slowly as batch sizes increase. This idea is captured in the yellow (dashed) custom trendline in the scatterplot.

Conclusionary, there seems to be an optimal region of batch sizes in the middle part of the line depicting the trend of the data points. Analyzing the scatterplot, this optimal region is located around the region 75 – 200, although small peaks are visible at 100 and 200. Before and after this region, the trendline increases more rapidly and cycle times seem to be larger (thus less optimal).

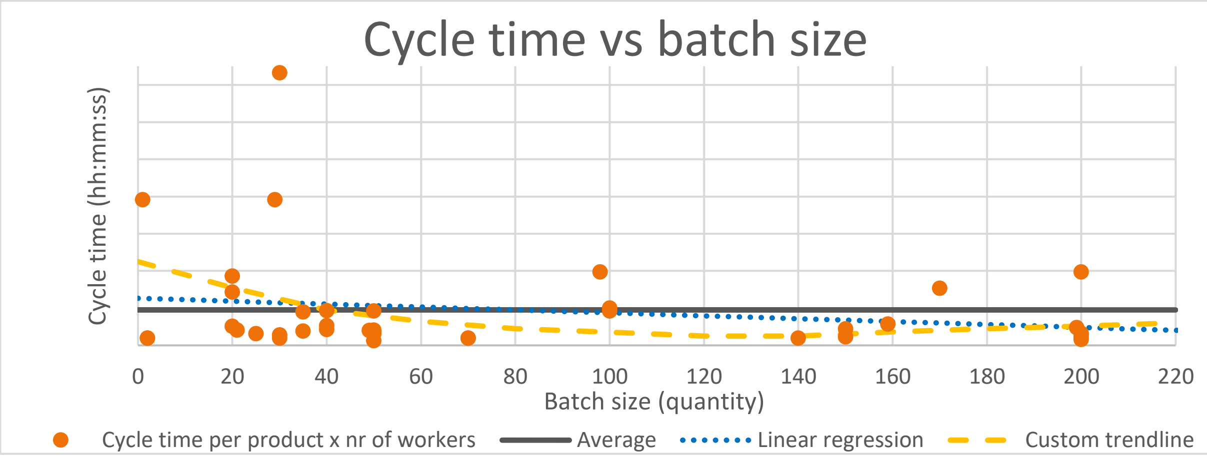


Figure 4-3: Scatterplot of the cycle time (per product x nr of workers) vs batch size for the assembly orders of the product mix representing the basic group. Chart axis with cycle times removed due to confidentiality.

Simple group – assembly

Pearson / Spearman correlation coefficient: -0.307 / -0.294
R^2 Linear regression line: 0.094

The scatterplot showing the batch sizes versus cycle times of the products within the simple group can be seen in Figure 4-4. The correlation coefficients both reveal a weak, negative correlation. Remarkable is that these correlation coefficients are higher than the calculated correlation coefficients for the product mix of the simple group and almost fall in the category of moderate correlation.

The distribution of data points looks totally different than the distribution in the scatterplots identified above. Overall, there seems to be a downwards trend. This downwards trend is confirmed by the regression line (dotted blue line), which clearly has a negative slope (but poor fit with the data). In the beginning, however, the cycle times seem to increase in the region zero to six. A reason for this increase could be that less setup, and thus setup time, is necessary for very small batches than for somewhat larger batches. Afterwards, a decreasing trend can be identified until a minimum has been reached at twenty-two. This decreasing behavior is probably due to the dividing of the setup time over more products.

Afterwards, the trend in the data points seems to start increasing. It is hard to determine the exact reason for this increase and the exact slope of this increase, as there are few large batches made. It could be as a consequence of distraction and boredom. More research should be done to investigate the exact reason. Moreover, it can be seen that the production planner uses some fixed batch sizes, indicated by having multiple data points on the same vertical line. A batch size of ten, twenty or thirty seems to be the favorite choice of the planner.

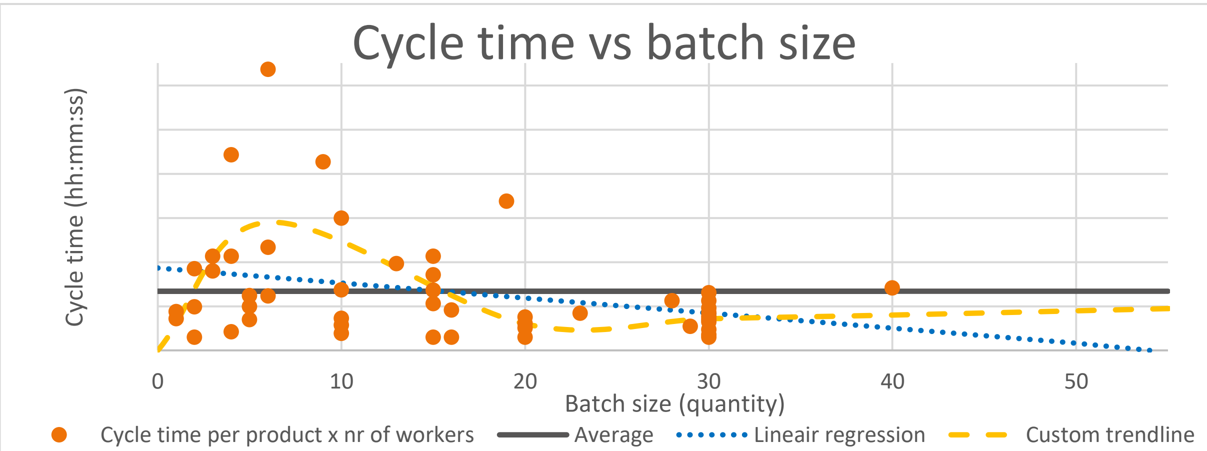


Figure 4-4: Scatterplot of the cycle time (per product x nr of workers) vs batch size for the assembly orders of the product mix representing the simple group. Chart axis with cycle times removed due to confidentiality.

The above described trends are depicted in the yellow (dashed) custom trendline in the scatterplot. Analyzing the behavior of the trendline, a batch size in the region 0-2 or 18-40 seems optimal as the line has its minima here. Before and after these points, the cycle time is larger than this region and, therefore, less optimal.

Medium group – paste

Pearson / Spearman correlation coefficient: -0.123 / -0.088
R^2 Linear regression line: 0.015

Figure 4-5 depicts the scatterplot of the cycle time versus batch size for the products of the medium group. A weak, negative correlation between the variables is revealed by both correlation coefficients. Analyzing the distribution of the scatterplot, it is remarkable that small batches are planned for these products, probably because of relatively low demand for this product. Besides, the spread in cycle times for small orders is relatively large, which could be due to low discipline of booking the orders.

Moreover, a negative trend can be discovered in the datapoints: from the upper left of the scatterplot to the lower right. This negative trend is confirmed by the linear regression line (dotted blue line), which clearly has a negative slope. The negative trend is probably again a consequence of the spreading of the setup time over more products. The trend in the datapoints with larger batch sizes is, however, less visible. There are only two datapoints with batch sizes of larger than twenty. Therefore, it is not possible to detect a trend for large batches and it can be assumed that the trend in cycle times is constant.

The above described trend is summarized in the yellow (dashed) trendline in the scatterplot. Analyzing the scatterplot and the trend(line), it seems optimal to make as large as possible batches. It must be noted, however, that it is hard to determine if there is a maximum batch size after which the behavior of the cycle times is not optimal anymore. This is because the trend in the orders with a large batch size is hard to determine based on (only) two orders. At the moment, it can be assumed that the trend continues and, therefore, there is no maximum batch size.

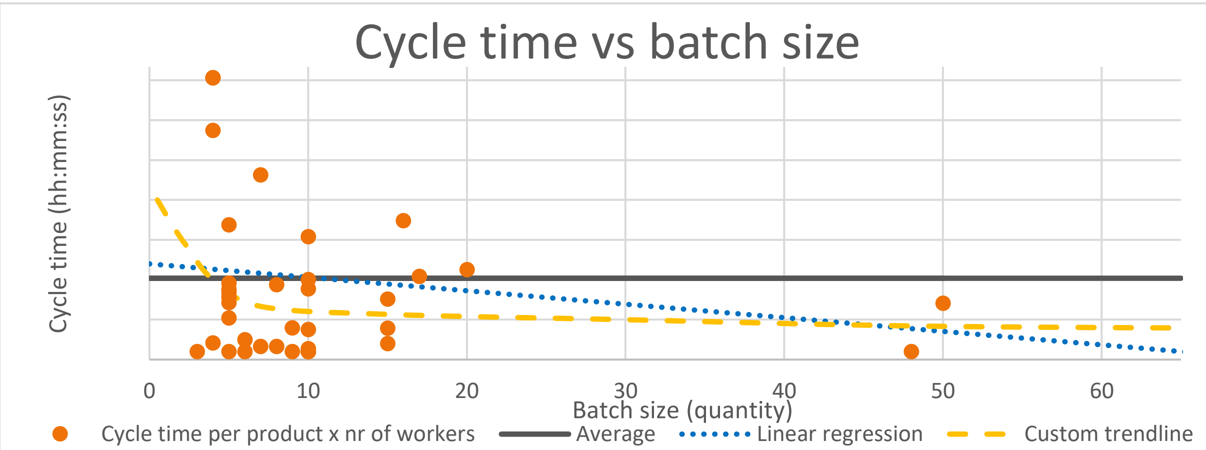


Figure 4-5: Scatterplot of the cycle time (per product x nr of workers) vs batch size for the paste orders of the product mix representing the medium group. Chart axis with cycle times removed due to confidentiality.

Medium group – assembly

Pearson / Spearman correlation coefficient: -0.195 / -0.328
R^2 Linear regression line: 0.038

The scatterplot of the assembly orders of the products of the medium group can be seen in Figure 4-6. The two correlation coefficients both indicate a negative, weak correlation between the variables (although Spearman correlation coefficient is close to the border of a moderate correlation). The distribution of the points seems almost exactly the same as the distribution in the scatterplot of Figure 4-5: almost all orders have a batch size lower than twenty and an overall negative trend in the datapoints (again confirmed by the blue, dotted linear regression line). As a finished product needs both a paste and assembly order, it is not remarkable that the trend is almost the same.

Because there are only two orders with a batch size larger than twenty, it is again difficult to determine the trend for these batch sizes. However, it can be seen that these two datapoints are positioned a bit higher than when a constant trend is used. Therefore, it is assumed that there is a slowly increasing trend here. However, it could be the case that there is a constant or even decreasing trend but that this is not visible due to the limited amount of data available.

The described trend is translated into a trendline and is the yellow dashed line in the scatterplot. As an almost similar distribution and trend is visible in the data, the conclusion is also similar: produce orders with an as high as possible batch size. This advice is given despite the slowly increasing trend. As this increase is very minor, it still seems good to produce as many as possible products.

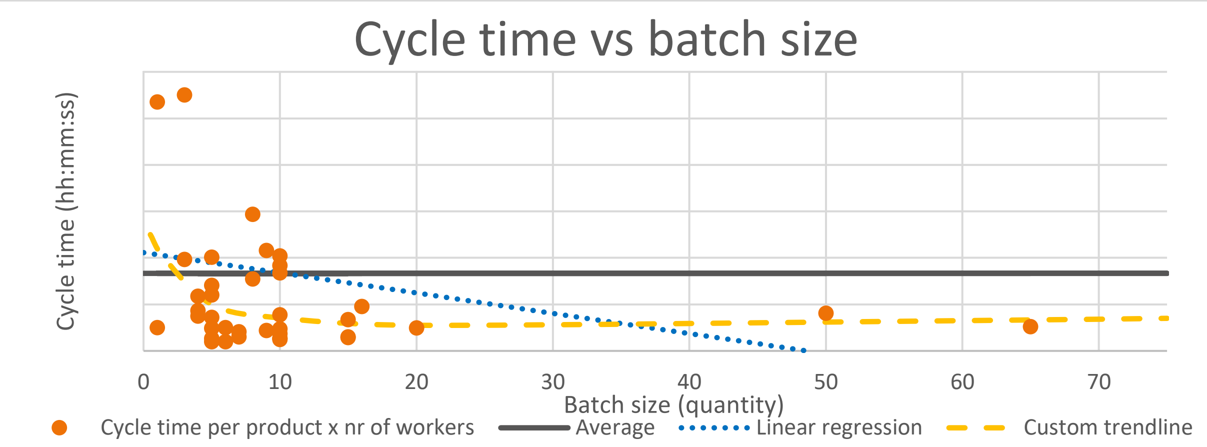


Figure 4-6: Scatterplot of the cycle time (per product x nr of workers) vs batch size for the assembly orders of the product mix representing the medium group. Chart axis with cycle times removed due to confidentiality.

Difficult group – assembly

Pearson / Spearman correlation coefficient: -0.081 / +0.158
R^2 Linear regression line: 0.007 & -0.118

Figure 4-7 depicts the scatterplot of the cycle time versus batch size of the product mix of the difficult group. First, it can be seen that that only small batches are planned by the production planner. As can be seen, only orders with batch sizes in the range of one to ten are scheduled. Second, some fixed batch sizes can be seen: orders with batch sizes of one, two, three or five are frequently planned.

Calculating the correlation coefficients, something remarkable can be seen. The Pearson correlation coefficient is negative, while Spearman correlation coefficient is positive (both weak correlation). The reason for this difference could be that the correlation is extremely weak and close to zero and, therefore, the sign changes.

Analyzing the scatterplot, however, two trends could be identified which is accordance with the correlation coefficients (although one can also argue that no trend can be identified at all):

1. **A downwards trend**. This is probably (again) a consequence of the spreading of the setup time over more products. Applying linear regression to the data, a regression line has been composed (blue dotted line). This linear regression line clearly shows a negative, downwards trend in the data. The line, however, does not fit the data well as the R^2 is low ($R^2 = 0.007$). Further analyzing the data, a custom trendline is drafted (yellow dashed line). This line shows a negative trend for very small batches (between zero and two) and a constant trend when batch sizes increase. As no larger batch sizes than ten are scheduled, it is hard to make a conclusion for this region. It is assumed, however, that the trend is constant.
2. **An upwards trend** depicted in the second (long dashed and dotted) green trendline. In general, the fit of the trendline is very poor, indicating by the negative R^2 of -0.118. A negative R^2 indicates that the model fit is worse than when using a straight horizontal line. Although this R^2 indicates a very poor fit with the data, it still seems to fit part of the data quite well (orders with small batch size).

One explanation of the upward trend could be boredom and quality rejections. The process of assembling these products is difficult and takes long as one needs to paste a very tight frame. For this pasting, one needs to be very concentrated and many mistakes can happen easily. As the frame fits very tight on the rest of the box, many times a quality issue can occur. Besides, the workers can get bored more easily as the process to assemble one box takes relatively long. Workers are more likely to talk and do other small chores, making the process more time consuming Combining these two factors, an upward trend in the data can be explained.

Analyzing the scatterplots and the two trendlines that are composed, it is hard to make a conclusion about the optimal batch size. The first, yellow (dashed) trendline indicates a decrease in cycle time as batch sizes increase till a batch size of 2. Afterward, a constant can be identified. This trendline would indicate to use as large as possible batch sizes. The second, trendline (green, dashed and dotted line), however, indicates an upward trend in cycle time as batch sizes increase. Therefore, the second trendline would indicate to use as small as possible batch sizes. Combining the conclusion of both trendlines and the distribution of the points, a batch size in the region of 2 till 6 seems optimal.

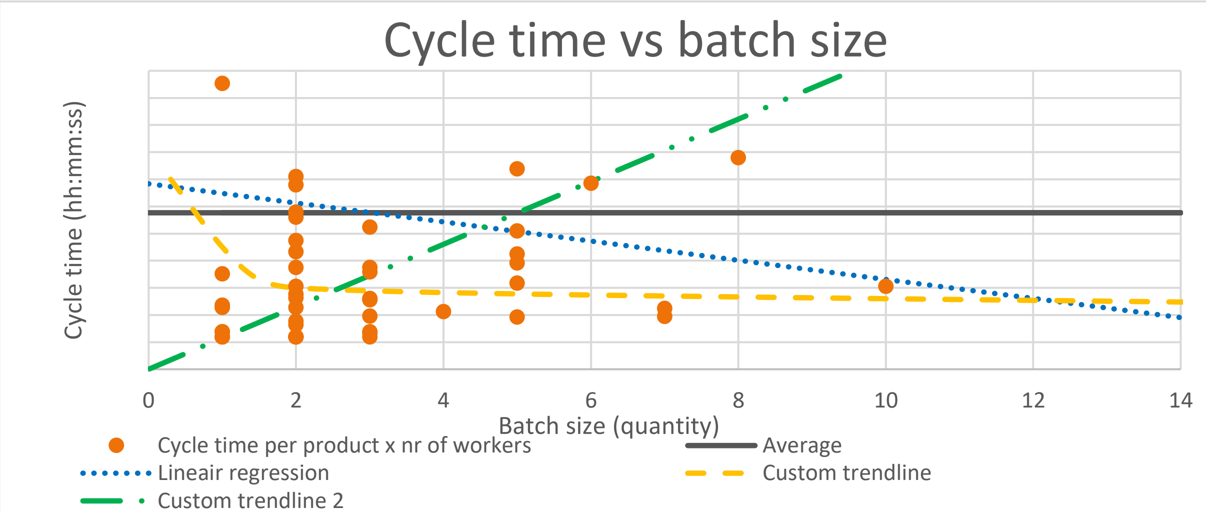


Figure 4-7: Scatterplot of the cycle time (per product x nr of workers) vs batch size for the assembly orders of the product mix representing the difficult group. Chart axis with cycle times removed due to confidentiality.

4.4.2 Goods receipt

Unloading

Pearson / Spearman correlation coefficient: 0.973 / 0.963 & -0.753 / -0.877
R^2 Linear regression line: 0.947 & 0.567

Figure 4-8 depicts the scatterplot of the manual time measurements of the unloading process of trucks arriving at the goods receipt. An upwards, positive trend can be identified in the data. This trend is confirmed by the correlation coefficient indicating a very high correlation between the time to unload a truck and the number of pallets contained within a delivery. Besides, the fit of the linear regression line (dotted blue line) with the data is remarkably good, confirmed by the high R^2.

Investigating the distribution of the data and using the trendline, a general rule for the unloading time can be identified consisting of a fixed time per delivery and a variable time per pallet. I identified the following rule (hh:mm:ss):

$$\begin{aligned} Total\ unloading\ time &= fixed\ time\ per\ delivery + variable\ time\ per\ pallet \times number\ of\ pallets \\ &= 00{:}03{:}20 + 00{:}01{:}00 \times number\ of\ pallets \end{aligned}$$

Adding the average time per pallet to the scatterplot (yellow points), a downwards sloping trend can be discovered. The correlation coefficients and the linear regression line (dashed green line) through these points confirm this downwards trend. The reason for this downwards sloping trend is probably the spreading of the relatively large, fixed time per delivery over all pallets.

Consequently, the average unloading time per pallet decreases. The decrease in unloading time, however, is not very large. Therefore, relatively little extra time is saved when unloading multiple pallets compared with unloading a small number.

Based on the scatterplot and the identified rule, I conclude that it is more optimal to have larger deliveries as there is a decrease in the average time per pallet as described above (although the decrease is small). Therefore, relatively large batches produced at the container-series line are more optimal for the unloading at the goods receipt as then more pallets need to be unloaded (which is optimal for the goods receipt). The number of pallets, however, must not be too large as this can result in a situation in which the pallets do not fit in one truck anymore and, consequently, more time is incurred by handling multiple trucks. Besides, the space at the goods receipt is limited and, therefore, not too many pallets can be unloaded and booked in the system at once.

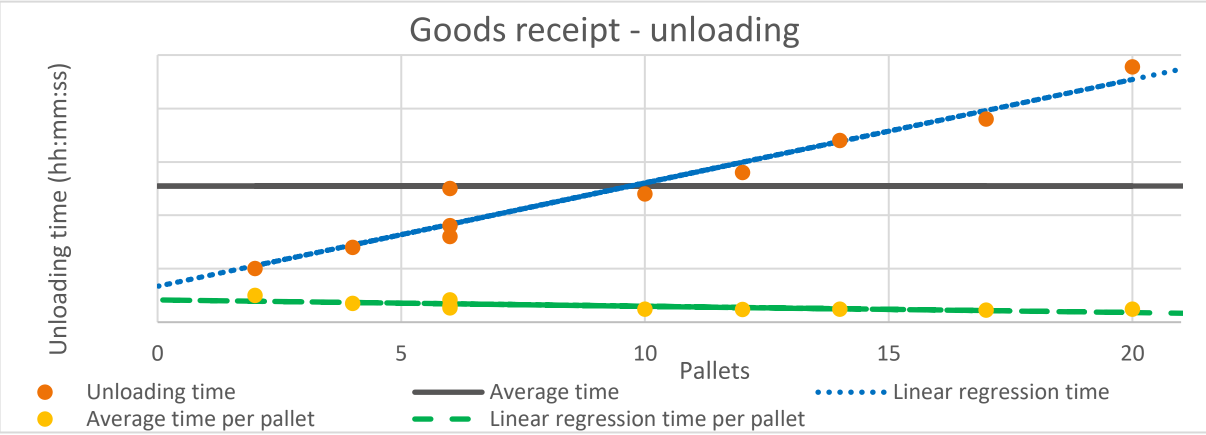


Figure 4-8: Scatterplot of the time to unload a truck at the goods receipt vs the number of pallets delivered. Chart axis with times removed due to confidentiality.

Checking and booking

Pearson / Spearman correlation coefficient: 0.666 / 0.569 & -0.449 / -0.480

R^2 Linear regression line: 0.444 & 0.202

The manual time measurements of checking the quality, quantity and booking the components in the system is mapped against the number of pallets/boxes that are checked. The result of this mapping can be seen in Figure 4-9. Analyzing the distribution of points, an upwards trend can be identified, confirmed by the positive slope coefficient of the linear regression line (dotted blue line). According to the R^2, the fit of the linear regression line with the data is medium. In addition, both correlation coefficients indicate a moderate correlation, although Pearson's correlation coefficient indicates almost a strong correlation.

As for the unloading time, a general rule consisting of a fixed and variable part for the checking and booking time can be identified. Analyzing the distribution of the datapoints and using the linear regression line, I identified the following rule (hh:mm:ss):

$$\begin{gathered} \textit{Booking and checking time} = \textit{fixed time per component} + \\ \textit{variable time per pallet/box} \times \textit{number of pallets/boxes} \\ = 00{:}03{:}00 + 00{:}02{:}00 \times \textit{number of pallets/boxes} \end{gathered}$$

Analyzing the identified rule and distribution of the data (both total and average booking time), it seems optimal to check and book in multiple pallets of a component at the same time compared with every pallet of a component separately. The reason for this is again the spreading of the fixed time over multiple pallets. As the proportion of fixed and variable time is different from the identified rule for unloading a truck, the relative time yield of checking and booking an extra pallet of a component is larger.

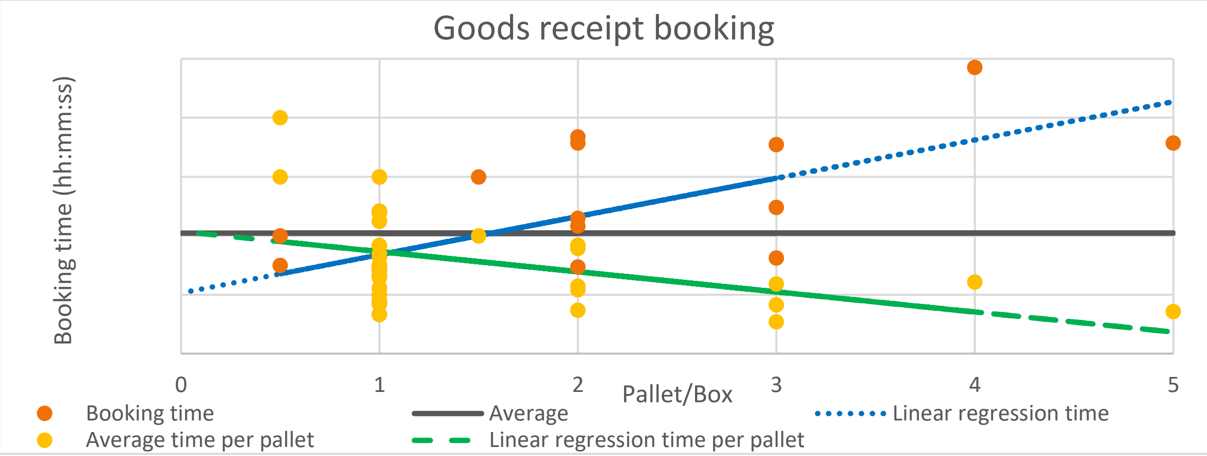


Figure 4-9: Scatterplot of the time to book in components at the goods receipt vs the number of pallets/ boxes that need to be booked in. Chart axis with times removed due to confidentiality.

4.4.3 Purchase quantities

Section D.3 in Appendix D contains tables with the overview of the purchase quantities, referenced in the subsections below. The tables only contain purchase quantities (minimum, maximum and fixed) of non-bulk components. As the list of parts with all components with their normal names is highly sensitive information, the names of the components are replaced with pseudo names.

Besides the purchase quantities, the purchase manager also provided some general information regarding the purchase of materials. The larger the order, the more discount is given on the order price (economies of scale for the supplier and, as a consequence, quantity discounts for ESS). Thus, the larger the purchase order the better for the purchase department (regarding costs). Due to the limited capacity of the components warehouse, however, large quantities are not always possible. Therefore, these are balanced when determining the size of a purchase order. As cost decrease with increasing quantity, it would be optimal for the purchase factor to produce as large as possible batches. Due to limited amount of time available, this subject is not treated further here.

Basic group

Table 25 in Appendix D contains an overview of the purchase quantities of the components used in the assembly of the products of the basic group. Analyzing the table, it can be noted that there are a lot of similarities of the components in all products of the simple group. In fact, Basic-1 (Basic-2) and Basic-3 (Basic-4) are the same product, with the exception that Basic-1 (Basic-2) is specific for one Dutch client and, therefore, another logo and manual is included in the product. As these are bulk components, these are not included in the overview and, as a consequence, have exactly the same components here. Besides the similarities, only a small amount per component is necessary for the production.

For the components of the simple group, only a minimum order quantity exists in the order quantities of hundreds or thousands. These minimum quantities are all round numbers except for component E (with a minimum quantity of 3096). It therefore seems logical to only produce somewhat larger batches of nice round quantities, for example in steps of 20. As there are no maximum or fixed order quantities, these do not have to be considered in the determination.

Simple group

The information of the purchase quantities of the component of the simple group can be seen in Table 26 in Appendix D. It can be seen that a lot more different components are necessary for the products in this group compared with the products of the basic group. The reason for this is that this group contains products that have different dimensions or colors, each with its own components (e.g., frames in different sizes and colors). For each product, only five different components are needed, of which one, two or three components per product is necessary. Only two components, components B and F, are needed in all products of this group.

Analyzing the purchase quantities, it is remarkable that sometimes the minimum purchase quantity is very low (only one) and sometimes the minimum purchase quantity is relatively high (couple of hundreds/thousands). Besides, there are no maximum or fixed order quantities for almost all components. There is only a rule in the order quantity of component B, for which the order quantity varies between 1000, 1500 and 2000. Further analyzing the purchase quantities and calculating the greatest common divisor (omitting purchase quantities of 1 and 756), I conclude that batch sizes divisible by 10 and increments of 10 seems optimal for the purchase of components.

Medium group

Table 27 in Appendix D depicts the purchase quantities of the components used in the assembly of products in the medium group. It can be noted that a lot of components of the products of the simple group are also needed for products in this group. Besides, it can be seen that only five components are necessary for producing one product, of which only two are not used for products in the simple group. The two components specific for this group are even the same for products with the same color and dimensions.

As Table 27 shows, there are no maximum or fixed order quantities for the components. Analyzing the minimum purchase quantities, it can be concluded that these are almost all round numbers (except for 756). Omitting the minimum quantity of 756, the greatest common divisor is ten. Since there are no further restrictions or specifics, a round batch size with increments of 10 seems optimal for purchase.

Difficult group

The purchase quantities of components of the difficult group is depicted in Table 28 in Appendix D. For this group, a lot of components of the simple group are also necessary in the assembly of the products. There are (only) five additional components needed, specific for the products of this group. Besides, it can be seen that some components are standard for the smaller versions (small and medium) and other specific for the larger versions (large).

As for the other groups, there are no maximum or fixed purchase quantities. The minimum purchase quantities are either relatively high (thousand or more) or relatively low (one). The minimum purchase quantities are almost all nice round number. Calculating the common greatest divisor, (10; omitting quantities of 1 and 756), it seems optimal to make batch sizes with increments of 10.

4.4.4 Components warehouse

To determine if more stock of components could be used than the currently available stock in the components warehouse, the utilization rate of the components warehouse need to be determined. Table 7 depicts respectively the total capacity (places), the total used places, the ideal utilization rate and the actual utilization rate. As the actual utilization rate of 88.26% is almost equal to the ideal utilization rate and is only theoretical, one can assume that the components warehouse is too full. Therefore, it can be assumed that only the current stock can be used for production and, as a consequence, this limits the batch size possible to what is only possible with the current stock.

Table 7: Number of places (used) and utilization rate of the components warehouse. Part of the data is censored due to confidentiality.

Total places	Total used	Ideal utilization rate	Utilization rate
[redacted]	[redacted]	90.00%	88.26%

To take into account the fact that some components are used across multiple products and some safety stock is desirable to handle uncertain customer demand, it is assumed that 80% of the available stock can be used for the production of products.

Basic group

Table 25 in Appendix D contains besides the purchase quantities also the stock level of the non-bulk components used in the production. As for all components except component C only one is needed in production, the stock level is equal to the number of products that can be assembled with it. Remarkable is that of some components there is enough on stock to produce, in theory, 3000+ products while for others only about 250 are available. Reason for this is the fact that some components are also used in the production of other products. Of the components, only components A, E and F are specific for the products in the simple group. Analyzing the current stock level and it is assumed that 80% of the stock can be used, I conclude that the maximum batch size possible is about 200 for Basic-2/Basic-4 and about 600 for Basic-1/Basic-3.

Simple group

The current stock level of the components of the simple group can be seen in Table 26 in Appendix D. Remarkable is that there is a large difference between the stock levels. Of some components, more than thousand are in stock while of others only a small number (one, three or four). Components with a large stock are components used in all (or many) products within this group. Components with a small stock are components used in specific products, for example products with specific colors (crème). Besides, one component only has a stock of 1. The reason for this is that this component is replaced by a newer version, of which there is enough stock. Analyzing these levels, I conclude that the maximal batch size considering stock is around 70 for Simple-1-(Small to Large), 40 for Simple-2-(Small to Large), 5 for Simple-3-(Small to Large) and around 80 for Simple-4-(Small to Large).

Medium group

Table 27 in Appendix D contains the stock level of the components used in this group. Analyzing these levels, one can see that for some components there is no stock at all. The reason for this is that these components are processed by ESS itself to other components. The fronts are grinded to “slijpfronts” and boxes are colored in the right color. As these processed components are needed in production, these must also be considered and are depicted in the column “Stock2” (summed over all colors).

Analyzing the stock levels, a large variation in stock level can be discovered. Large stocks are held of some components, especially the components used in the simple group, and small stocks are held for other components. Moreover, there is even one component of which only one is in stock. This is again due to the switching to a newer version of the component (of which there is enough stock) and, therefore, can be omitted here. Further analyzing the stock levels, two points stand out. First, the color-specific slijpfronts are often the bottleneck of producing larger batches. Second, a trend in magnitudes per dimension can be discovered. Assuming that this trend also applies for components that are currently not on stock and the fact that 80% can be assigned, the maximum possible batch size is 15 for the small and medium dimensions and 30 for the large dimensions.

Difficult group

The current stock level of the products in the difficult group can be seen in Table 28 in Appendix D. As the medium group, some components are processed further and, therefore, these must also be considered in the stock. These stock levels are aggregated and are depicted in the column “Stock2”.

Analyzing the stock levels, no real trends can be identified. Some components do have enough stock to produce 50 or more products, while there are also products of which 0 or only 4 can be produced. As no real trend can be identified, no product-specific maximal batch sizes could be determined. The limited components are the bases of the boxes, of which only around 10 are in stock. Therefore, this is assumed to be the overall maximum batch size for this group.

4.4.5 Picking

Pearson / Spearman correlation coefficient: -0.641 / -0.077 & -0.283 / -0.963
R^2 Linear regression line: 0.411 & 0.080

To investigate the relation between batch size and the pick process, the pick time has been measured manually for one day. Figure 4-10 depicts the result of the measurements plotted against the respective production quantity of the pick order. Remarkable is that there are a lot of orders with a small production quantity (there is even an order of one) and less orders with a large production quantity (only one with a production quantity greater than hundred).

Calculating and plotting the average time per production quantity, a negative relation can again be identified. Almost all points lie along the calculated linear regression line showing a negative relation except for one point (with production quantity of one). The reason this point does not nicely lie along the line is that the total time is equal to the average time as the production quantity is one and, therefore, the total time is not spread over a large production quantity. It still seems, however, that there exists a (weak) negative relation between the average time and production quantity, also confirmed by the linear regression line (although showing a poor fit indicated by the R^2). This negative relation is probably due to the fact that the fixed time per pick location (driving time, time to remove the pallet from the rack) can be spread over a large production quantity.

Spearman correlation coefficient shows a very strong correlation between the average time and production quantity while the other, Pearson, shows a weak correlation between these two variables. Reason for the difference could lie in the fact that Pearson can be used to detect only a linear relation between variables, while Spearman can also investigate other forms of correlation. Therefore, one could argue that there does not exist a linear relation (as shown by the green, dashed line) but another kind of relation, for example the one depicted by the purple, dashed and dotted trendline. The decrease in average pick time, however, seems not to be very large with increasing production quantity. Therefore, it seems not to be very beneficial for the average pick time to use larger batch sizes, although a very low batch size (smaller than five) does have a negative influence on the average pick time.

Concluding, there seems to exist a relation between the (average) pick time and production quantity. The average pick time seems to decrease slowly with an increasing production quantity. Therefore, larger production batches seem to be a bit more beneficial for the pick time than smaller batch sizes. From a batch size of 5, the extra decrease in pick time is relatively low and, therefore, a batch size of greater than or equal to) 5 seems optimal for the pick process.

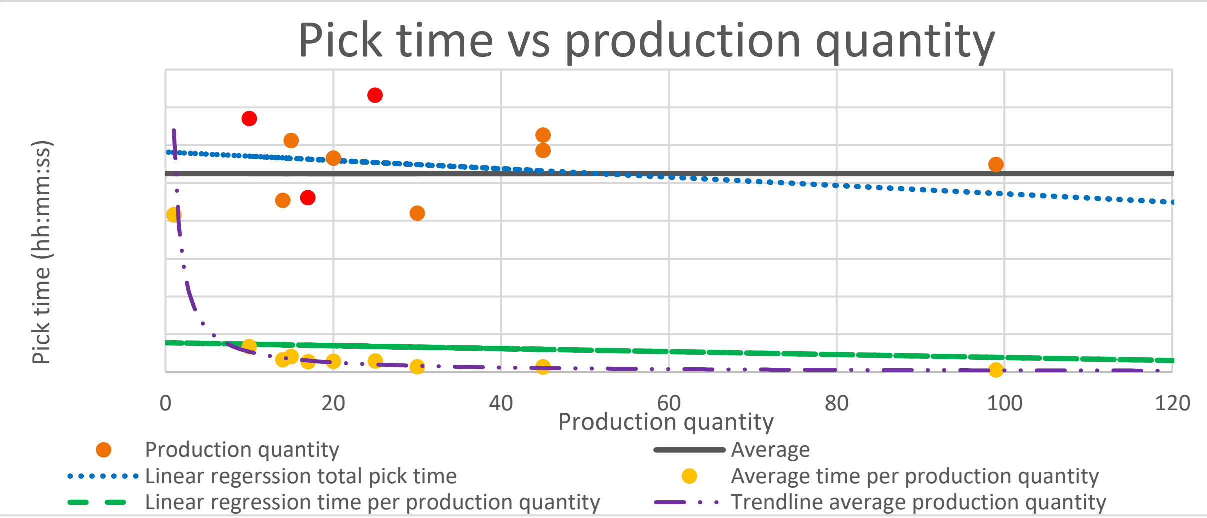


Figure 4-10: Scatterplot of the time to pick components at the components warehouse vs the number of products for which the pick order is picked. Chart axis with times removed due to confidentiality.

4.4.6 Finished goods warehouse

Table 8 depicts the number of total and used places in the finished goods warehouse including utilization rate and ideal utilization rate. It can be seen that the utilization rate of this warehouse is much lower than the utilization rate of the components warehouse. Moreover, the actual utilization rate is much lower than the ideal utilization rate. This means that more places than the places reserved for the products could be used when larger batch sizes are more optimal as there is enough capacity left. This is, however, not the starting point as this is seen as less optimal than the normal reserved places for the products.

Table 8: Number of places (used) and utilization rate of the finished goods warehouse. Part of the data is censored due to confidentiality.

Total places	Total used	Ideal utilization rate	Utilization rate
[redacted]		90.00%	68.14%

Table 29 in Appendix D contains information regarding the finished goods warehouse and shows among others the number of products per pallet and the number of pallets per finished product that could be stored in the warehouse.

Basic group

Because the dimensions of the Basic-1/3 and Basic-2/4 are (almost) the same, the same number of products fit on one pallet, namely forty. For both products, there is one (and when needed maximal two) pallet places reserved and, thus, a maximal of eighty products can be stored in the warehouse. For the Basic-1 and Basic-2 products, however, more products can be stored. The reason for this is that these products are only made for a specific Dutch distributor and, therefore, are only stored shortly in the own warehouse before being transported to the warehouse of the Dutch distributor. As a consequence, there is actually no maximum for these products. Increments of 4 seems optimal for the batch size, as there fit 4 products per layer. For Basic-3 and Basic-4, the maximum possible batch size is 40 or 80, as then respectively one or two full pallets are stored. For the batch size increments of 4 seems optimal, as 4 products fit per layer.

Simple group

As can be seen in Table 29, the number of products per pallet and the maximal number of pallets in the warehouse is only dependent on the dimensions of the product and not on the colors. Of every color, there fit maximum one pallet in the warehouse containing 117, 48 and 36 products for respectively small, medium and large dimensions. Therefore, these numbers are seen as the maximum batch size for the warehouse. Per pallet layer, 9 (for small) and 4 (for medium and large) fit. As it is seen as more optimal to fill complete layers, I recommend using batch sizes with increments of respectively nine and four for the products in this group.

Medium group

Different than the products of the previous groups, the products within this group are not stored on a pallet. Instead, these are stored on a collective storage buck. On the collective storage bucks, different products are stored mixed. Products that do not have an own location are just placed on top of the products already present here. Per color and per dimension, the head of the finished goods warehouse estimated that around 5-6 products maximal can be placed on the collective storage bucks. Therefore, this is seen as the maximal batch size for this factor. As no layers have to be filled and it is about small numbers, I do not advise fixed increments.

Difficult group

As the medium group, the products of this group are stored on the collective storage bucks and a maximum of 5-6 products of each color and dimension do fit on these. Therefore, the advice of batch sizes for this group is the same as for the previous group: maximal 5-6 products per color per dimension are possible, without fixed increments.

4.4.7 Sales

Information regarding the demand used for the sales factor can be seen in Table 30 in Appendix D. Per product, the demand of the previous two years, the demand till June of this year, and the forecasted demand (averaged per month and year) is provided. The demand for 2021 is assumed to be the combination of the forecasted demand (when available) and two times the demand of 2021 till June. Besides, the trend in demand is taken into account. From an interview with the production planner, it is seen as optimal to produce batches to fulfilled demand of one to two months. Therefore, it is assumed here that 1.5x demand must be met with one order (except Basic-1 and Basic-2).

To gather information regarding sales quantities that are optimal for the sales, interviews with the export manager of both Germany and France were performed. These export managers have been interviewed as the products of the container-series are sold well in these areas. The main findings in the interviews with the export mangers were that these products are not sold in fixed quantifies, are luxurious products, of which can be delivered late and are almost always ordered one at a time. For Basic-1 and Basic-2, an interview with the responsible sales employee has been performed to identify optimal sales quantities as these products are specific for one Dutch distributor.

Basic group

Analyzing the demand, a great distinction between the products within this group can be identified. Starting with Basic-1 and Basic-2, it can be seen that the demand slightly increases to an expected demand of respectively around [redacted] and [redacted] for 2021. Speaking with the sales employee responsible for the Dutch distributor, it is known that around [redacted] of Basic-1 are ordered each month and between [redacted] and [redacted] for Basic-2 with an interval of 1-1.5 month(s). Combining this with (1) the fact that these products are specific for this client and (2) the monthly forecasted demand (see Table 30 in Appendix D), I conclude that the optimal batch size for the sales is around 200 for Basic-1 and 30 for Basic-2.

Analyzing both historical and forecasted the demand for Basic-3 and Basic-4, it can be seen that about the same demand compared with last year is expected for Basic-3 and a slight decrease for Basic-4. Combined with information of the export managers and the fact batches to fulfill one and a half month's demand, a batch size around respectively 30 and 10 is optimal for the sales.

Simple group

Analyzing the demand levels of the products within this group, a pattern can be discovered per dimension. There are, however, exceptions that fall outside this pattern. Grouping the colors per dimension together, the following pattern has been identified (except for variant 3 all dimensions, variant 2 small and variant 4 large): a batch size around 7 for the small versions, around 27 for the medium and around 18 for large versions. For the variant 2 small and variant 4 large, a pattern in batch size of respectively around 11 and 22 is identified. For variant 3, a batch size of around 2 for small and around 3 for medium and large is identified. These patterns are assumed to be optimal for these products considering the sales.

Medium group

For the medium group, no forecasted demand is available. Therefore, the analysis of this group is only based on the historical demand, the pattern visible in this demand and the findings from interviews. An analysis of these both show that almost all products within this group are ordered relatively infrequent and on at a time, except for five products: medium and large of variant 1 and variant 4 and large of variant 2. These are ordered a little more frequent and, as a consequence, a somewhat higher batch sizes is optimal here. Further analyzing the demand, the batch sizes optimal for these products are (assuming producing for one and a half month): 8 (medium variant 1), 3 (large variant 1), 2 (large variant 2), 15 (medium variant 4) and 7 (large variant 4). For the other products, a batch size of 1 is optimal. As these levels are all relatively low, one could also argue to produce for three months and use double batch sizes.

Difficult group

The forecasted demand is only available for products of variant 2 within this group. Analyzing the forecast demand for this variant and the historical demand for all products within this group, a pattern per variant can be seen. In three of the four variants (all except variant 3), the medium dimension is the most popular dimension, followed by large. For variant 3 products, no pattern can be discovered and the demand for all dimensions is low and (almost) equal.

Further analyzing these demands, no real general pattern per dimension can be identified as the demand does differ a lot. Therefore, each product gets its own advice regarding optimal batch size. This advice is depicted in Table 9, assuming production for one and a half month. As the medium group, one could consider producing for three months and use double the advised batch sizes.

Table 9: Overview of the advice for batch sizes for products within the difficult group, assuming production for 1.5 months.

	1	2	3	4
Small	2	3	1	1
Medium	5	8	2	9
Large	4	5	1	3

4.4.8 Conclusion batch sizes

Table 31 in Appendix D summarizes the batch sizes optimal for each factor. Combining the information of all factors, a conclusion regarding the batch sizes could be drawn. Analyzing this information, it could be seen that there are factors that go well together and factors that are incompatible or contradictory. In these cases, the more important factors are giving priority to other factors. Factors seen as more important than others are station cycle time, components and the sales. Reason for the importance of these factors are respectively cycle time reduction is a goal (because this increases the capacity of the line, see Chapter 1), no more components than are in stock can be used and much lower/higher batch sizes than the sales means unable to deliver quickly or unnecessary high stock. Sometime, however, the important factors are also incompatible and a trade-off has to be made. In these cases, an own consideration is made.

In addition, the maximum reserved places of some products are omitted as it would be more optimal to make larger batches. However, this factor is taken into account and compensated by the fact that some other products in the group have relatively low batch sizes and do not use the maximum number of places. As it was not possible to set one batch size per group due to the great variety within certain factors, each product in the group has been assigned an own batch size and provided in Table 10. These batch sizes are based on the analyses described in the previous subsections and summarized in Table 31 in Appendix D.

As there are no fixed batch sizes for these products, the expected effect compared with the current batch sizes is hard to determine. To make some form of comparison possible, the average cycle time of each product is compared with the cycle time of the proposed batch sizes. The average cycle time per product is gathered using the cycle time tool, the cycle times of the proposed batch sizes are retrieved from the trendlines in the scatterplots (see Section 4.4.1). Sometimes, averages that are unrealistic low or high are retrieved by the tool, possibly because of a combination of too less data and poor discipline of the worker on the table to report the order correctly. These unrealistic low and high averages are manually replaced by values which are more plausible. Moreover, a weighted average with weights based on demand of 2020 is used to calculate the decrease relative to the averages. Reason for this is that it is believed that differences in cycle times for fast flowing products (products that are produced and sold more often than other products) are more important than differences in cycle times of slow flowing products.

A calculation of the (weighted) differences results in a decrease in the cycle times of the basic, simple and difficult group (see Table 10). These decreases are almost the same as the expected decreases described in Chapter 1.

Table 10: Overview of the proposed batch size per product.

Basic		Simple		Medium		Difficult	
		Simple-1-Small	9	Medium-1-Small	1	Difficult-1-Small	2
		Simple-2-Small	11	Medium-1-Medium	8	Difficult-1-Medium	5
		Simple-3-Small	2	Medium-1-Large	3	Difficult-1-Large	4
		Simple-4-Small	9	Medium-2-Small	1	Difficult-2-Small	3
Basic-1	200	Simple-1-Medium	28	Medium-2-Medium	1	Difficult-2-Medium	7
Basic-2	30	Simple-2-Medium	28	Medium-2-Large	2	Difficult-2-Large	6
Basic-3	40	Simple-3-Medium	2	Medium-3-Small	1	Difficult-3-Small	1
Basic-4	20	Simple-4-Medium	28	Medium-3-Medium	1	Difficult-3-Medium	2
		Simple-1-Large	18	Medium-3-Large	1	Difficult-3-Large	1
		Simple-2-Large	18	Medium-4-Small	1	Difficult-4-Small	1
		Simple-3-Large	2	Medium-4-Medium	15	Difficult-4-Medium	9
		Simple-4-Large	24	Medium-4-Large	7	Difficult-4-Large	3
-15,4%		-13,9%		0,0%		-19,3%	

There is, however, one group (medium group) for which there is no difference visible between the current batch sizes and the proposed batch sizes. This shows that ESS is using already optimal batch sizes for this group. Overall, a decrease of 12% in cycle times is realized. This 12% is close to the goal of overall decrease of about 14% set in Chapter 1. Because there is no decrease in the medium group, the goal of about 14% is not completely met.

Due to limited executing time, the precise effect of these more optimal batch sizes in practice could not be evaluated. However, this could be done in the future by ESS itself. By using the proposed batch sizes in practice and calculating the cycle times with the help of the cycle time tool, the new cycle times could be determined. Comparing these with the current cycle times, a conclusion can be drawn regarding the decrease in (average) cycle times. Based on this conclusion, it can be determined if the goal of decrease in cycle time for each group has been reached or not.

The analysis showed that, in three of the four groups, a reduction in cycle times can be achieved by changing the batch sizes to more optimal batch sizes. For the other products in the groups and, thus, of the assembly line, it is recommended to use a similar procedure as executed above to determine the optimal batch sizes. As there are no general batch sizes found for the groups, no batch sizes for the other products of the line can be proposed and the analysis as performed above has to be performed again with the information of the new products.

4.5 Sensitivity analysis

To validate the results of the batch sizes determined, a sensitivity analysis is executed. More specific, the effect on batch sizes of certain scenarios are analyzed in more detail. These scenarios represent a change in one factor, whose effect on batch sizes is investigated. Comparing this sensitivity analysis with the different types of sensitivity analyses (see Section 4.2.4), this analysis does fit to the category mathematical models. The following two scenarios are investigated:

- **Demand**. Due to the fast growth of the company and the arrival of Hansgrohe, the demand can increase rapidly on the short-term. The effect of an increase in demand of 5%, 10% and 20% is investigated.
- **Available components**. In the determination of batch sizes, it is assumed that 80% of the stock can be used to assemble products. Especially for components used across multiple products, this percentage could be too high. Therefore, the effects of a decrease of 25%, 50% and 75% on the maximum number of products that can be assembled (80% of the stock) is investigated.

4.5.1 Demand

Table 32 in Appendix D contains the changes in batch sizes and cycle times due to these changes in batch sizes (assuming the same production frequency). It can be seen that both a 5% and 10% increase in demand has relatively little influence on the proposed batch sizes. On the products in the basic group, there is either no or a small difference in the batch sizes.

In the other groups, there are either no or some small increases (of only one or two products) compared with the original situation. Comparing the weighted differences per group (Table 11), it can be seen that this new situation is almost the same or slightly better for three of the groups compared with the original situation. Only for the medium group, a great decrease in weighted cycle times can be seen. Reason for this is that the demand is limiting the batch sizes, while it is more optimal for the cycle time to produce slightly larger batches.

As expected, a 20% increase in demand results in the biggest change in batch sizes and cycle times. Compared with the original situation, the increases in batch sizes are relatively minor. There are even products for which the batch sizes are unchanged with the original situation. These are almost all products which have low demand in the original situation. Comparing the weighted averages in cycle times of each group (see Table 11), somethings remarkable can be seen. For all groups except the basic group, there is either a small or no improvement visible in cycle times compared with the previous situation. For the basic group, however, a deterioration compared with the previous and original situation can be seen. Reason for this is that the larger batch size of Basic-1 is worse for the cycle time of this product. This larger batch size, however, must be made as otherwise demand is not met.

Table 11: Weighted difference in cycle times for the four groups in changes in demand of respectively 5%, 10% and 20%.

Group \ Demand change	0%	+5%	+10%	+20%
Basic	-15.4%	-15.4%	-16.3%	-4.4%
Simple	-13.9%	-14.9%	-14.6%	-15.2%
Medium	0.0%	-2.2%	-2.2%	-2.2%
Difficult	-19.3%	-19.0%	-20.1%	-20.4%

4.5.2 Components

The differences in batch sizes and cycle times due to a decrease of 25%, 50% and 75% in the available components can be seen in Table 33 in Appendix D.

Decreasing the available components with 25% and 50% result in a situation in which almost all of the proposed batch sizes are still possible with these decreases. Only some of the large batch sizes are affected and lowered. Analyzing the weighted decreases in cycle times per group (see Table 12), it can be seen that these two situations are very comparable with the original situation. Only small changes in these weighted differences can be seen but these are within 2% point range.

As expected, a decrease of 75% in the available components has a great influence on the proposed batch sizes. However, not all products are affected by this decrease. Especially products with a high initial batch size or from which already small batches are made due to the scarce components are affected. The weighted differences in cycle times per group (see Table 12) show that this situation is much worse compared with the original situation. In two of the four groups, there is even a large increase of around 20% visible compared with the current averages. Only for the basic group, these new batch sizes are more optimal.

Table 12: Weighted difference in cycle times for the four groups in changes in components of respectively -25%, -50% and -75%.

Group \ Components change	0%	-25%	-50%	-75%
Basic	-15.4%	-15.4%	-15.4%	-22.0%
Simple	-13.9%	-13.9%	-15.8%	+21.7%
Medium	0.0%	+1.9%	+2.9%	+25.4%
Difficult	-19.3%	-19.3%	-18.6%	-14.9%

4.5.3 Conclusion sensitivity analysis

Having analyzed the changes in batch sizes and, as a consequence of these changes, the cycle times, I conclude that small changes in certain factors do not affect the batch sizes, cycle times and weighted differences of the cycle times of each group heavily. Thus, batch sizes which are close to the proposed batch sizes could be used and will have limited (and maybe even a positive) effect on the reduction in cycle times. Too large deviations, however, could lead to an increase in cycle times and are, therefore, not desirable.

4.6 Conclusion

In this chapter, batch sizes for four product groups were determined. First, literature was analyzed to formulate the approach: determining batch sizes based on historical data and compare these with batch sizes optimal for other parts of the process. These other parts were identified by interviews with stakeholders and applying both TOC and VSM to the production process of ESS. Gathering and analyzing the information of all factors, product-specific batch sizes have been identified. These batch sizes result in a 12% decrease in cycle times compared with the product-specific average cycle times of the products in the groups. To validate the results, a sensitivity analysis has been performed in which changes in demand and available components have been investigated. The result of this analysis is that small changes in certain factors do not have a large effect on the results. Therefore, batch sizes which close to the proposed batch sizes could be used and will not affect the reduction percentages heavily.

5. Current quality issues

This chapter describes the tool that has been made to give insight in the quality issues. The outline of this chapter is as follows. Section 5.1 describes the approach that is used to build the tool. Section 5.2 contains the necessary literature used in building the tool. The main features and sheets of the quality issues tool are described in Section 5.3. Section 5.4 contains the most important results of the tool. Section 5.5 provides the analysis of the results and recommendations that have been drawn following the results. Finally, Section 5.6 describes the conclusions and contributions of this chapter.

5.1 Approach

To give insight into the reasons and origin of the quality issues, a tool is made in Excel using VBA. This tool includes visual elements to ease analysis and see the performance of the suppliers in one overview. This tool will be made flexible to be able to handle new data of new periods. This way, periodic analysis of the quality issues will be made as easy as possible.

The aim of the tool is threefold: (1) give ESS insight in the (frequent) reasons for quality rejections, (2) give ESS insight in the performance of different suppliers, which can be used to take further actions and (3) use the information about quality issues in the process of finding solutions to encounter fewer quality issues on the line.

5.2 Literature

For the construction of the quality issues tool, no new knowledge is needed. As this chapter only analysis the quality issues, the reasons and their origins, no literature is needed about supplier's performance or how it can be improved. This will be part of the next chapter, in which solutions are proposed to encounter fewer quality issues at the line. Therefore, literature on this subject will be part of the next chapter (Section 6.2.2). Besides, the way of visualizing data (Section 3.2.1) can directly be used for the construction of this tool. Thus, no new literature study is performed and the results of Section 3.2.1 are used.

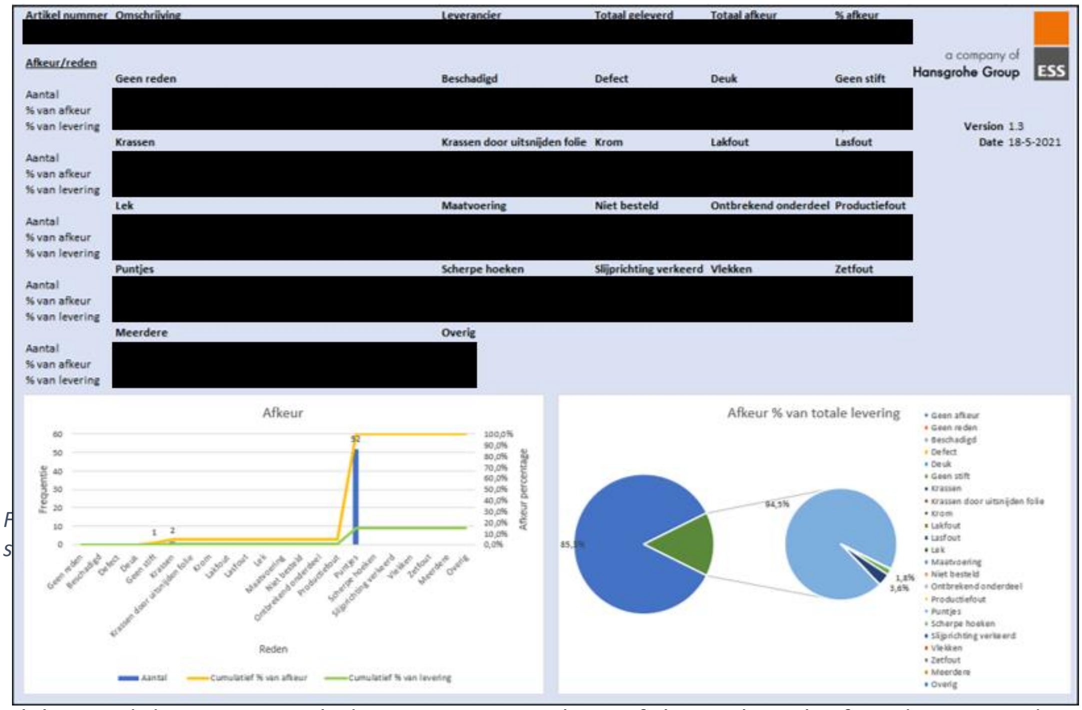
5.3 Quality issues tool

The constructed quality issues tool consist of nine sheets, each sheet having its own function. The first sheet contains data about quality rejections of all lines that are not the consequence of an action of ESS and sent back to the supplier. Rejections of components representing low values are not worth sending these back to the supplier and are, therefore, not part of the data. The second and third sheet contain information about the delivery of goods by two specific suppliers (pseudo names): Supplier 1 and Supplier 2. As these two suppliers deliver (almost) all components for the container-series line, only the data of these two suppliers is added to the tool.

In the next three sheets, the information of the first three sheets is filtered on a specific line (in this case line 5). Because there is no easy way to sort out the data for only a certain line 5 automatically, the user must manually filter and copy the data for a certain line to these sheets. Besides, all the data older than a certain date are filtered out (both data about delivery and quality rejections), as the quality manager started to add reasons to the quality rejections recently (since 23-04-19). The filtering of the information can be performed with the filter option in Excel on the description column. On the filtered quality rejections, another action is necessary. To perform analysis on the reasons, the reasons must first be standardized. Based on the data, a group of twenty-two reasons are identified and the existing rejections have been assigned one of these reasons (see Appendix E).

The next sheet is one of the two main sheets and contains a dashboard which can be seen in Figure 5-1. By selecting a component ("Artikelnummer") in the dashboard, the tool automatically finds all rejection bookings in the data including the reason for rejection. Moreover, the tool searches how many components have been delivered. Based on these two measures, new measures are calculated (percentage values) and graphs are updated. These graph types are based on the best way of visualizing data (Section 3.2.1).

If the user wants to have an overview of the rejections and quantity delivered of all components, the user can produce this overview with the help of another screen within the tool. The dashboard of this sheet is depicted in Appendix E. The results of this sheet are provided in the next section. By pressing the button "Load data", the tool automatically finds and calculates all measures (total delivered, rejection per reason) and writes this to the sheet. When the measures of all products are calculated, the measures and graphs in the dashboard are updated. The graphs are based on the graph types that best visualizes data (Section 3.2.1). Among others, the frequency of reasons and performance of the suppliers is visualized.



A more elaborated description including more screenshots of the tool can be found in Appendix E. This Appendix contains an explanation of the sheets and the way the sheets are filled with the correct information with the help of VBA code.

5.4 Results

This section contains the main results of the quality issues tool. Only the measures of the rejections and quantity delivered of all components are provided in this section as it is not possible to place the results of all components separately. Tables 13 till 15 provide numerical information about the rejections split by supplier or reason. Figures 5-2 till 5-4 show the frequency and top fifteen of the rejection percentage. Lastly, Figures 5-5 till 5-8 provide the results of the performance and reasons for rejection per supplier. Some results are anonymized because of confidentiality.

Table 13: General measures calculated in the quality issues tool.

Total components	Total delivered	Total rejected	% Total rejected / total delivered	Total Supplier 1	Total Supplier 2	Total other
[redacted]						
				[redacted]		

Table 14: Components with and without quality rejection, split per supplier.

Components without rejection(s)					
Total	%	Supplier 1	% (relative to total Supplier 1)	Supplier 2	% (relative to total Supplier 2)
[redacted]					

Table 15: Overview of the occurrence of a certain reason for quality rejection.

Components with rejection(s)					
Total	%	Supplier 1	% (relative to total Supplier 1)	Supplier 2	% (relative to total Supplier 2)

[redacted]

Legend

A	Production error	G	Dots	M	Grinding direction	S	Dimensions
B	No reason	H	Leak	N	Not ordered	T	Mounting error
C	Others	I	Welding error	O	No pin	U	Damaged
D	Scratches	J	Multiple	P	Malfunction	V	Missing part
E	Painting error	K	Stains	Q	Dent		

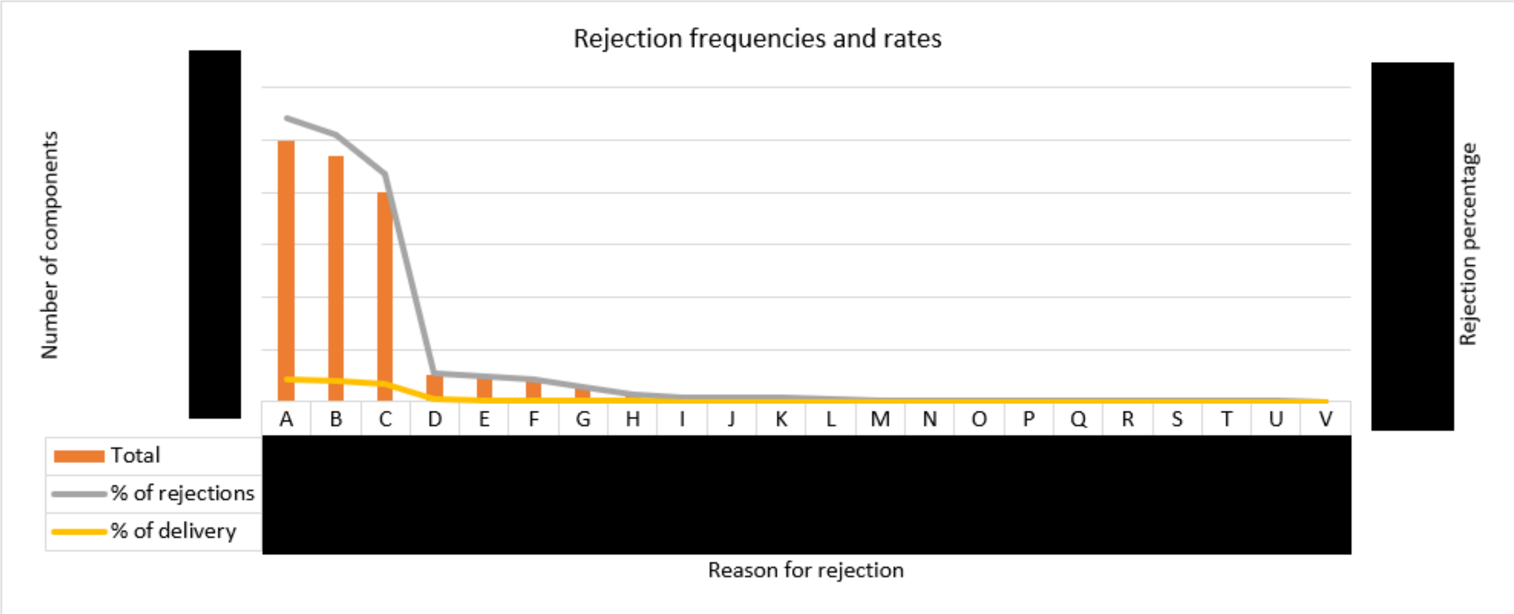


Figure 5-2: Overview of the frequency and percentages per reason, letters corresponding with reason in legend (see above the figure). Chart axis removed due to confidentiality.

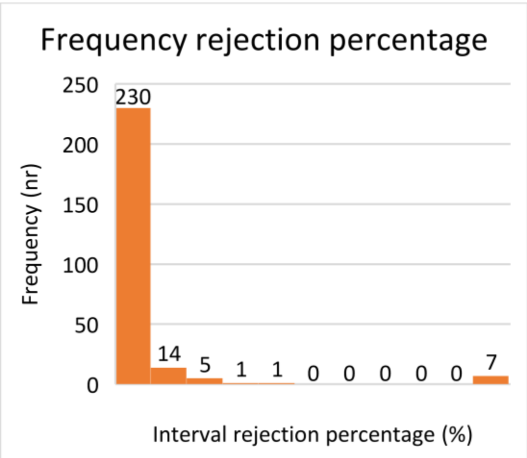


Figure 5-3: Frequency of the quality rejection percentage per interval (over all components of line 5). Chart axis removed due to confidentiality.

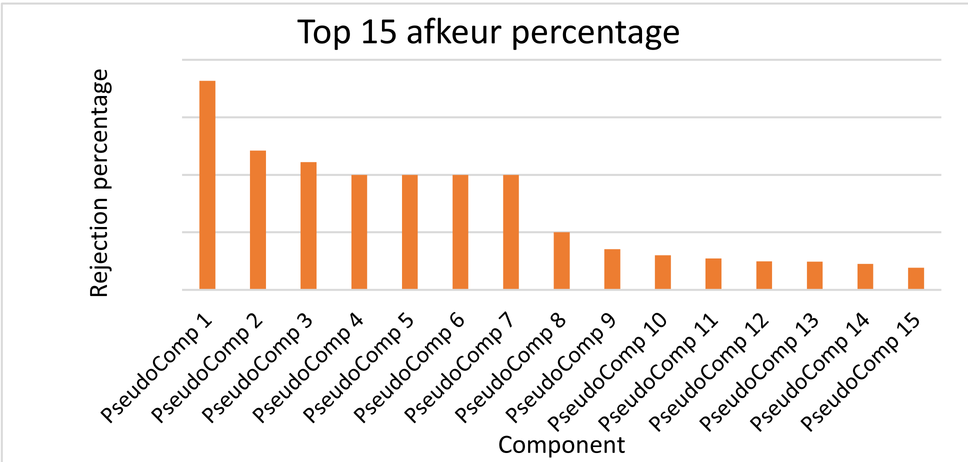


Figure 5-4: Overview of the top 15 quality rejection percentages (over all components of line 5 and pseudonyms used for components due to confidentiality). Chart axis removed due to confidentiality.

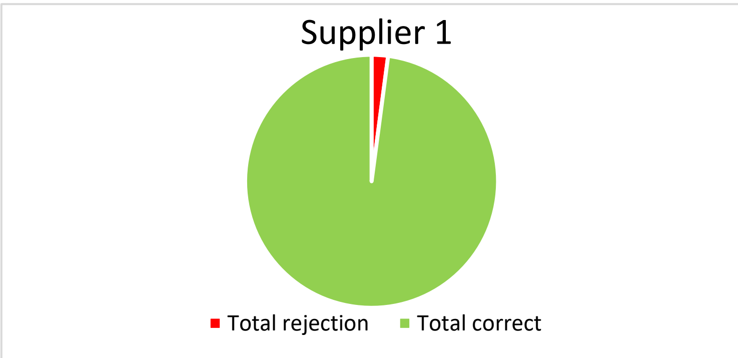


Figure 5-5: Overview of the performance of Supplier 1. Exact percentages removed due to confidentiality.

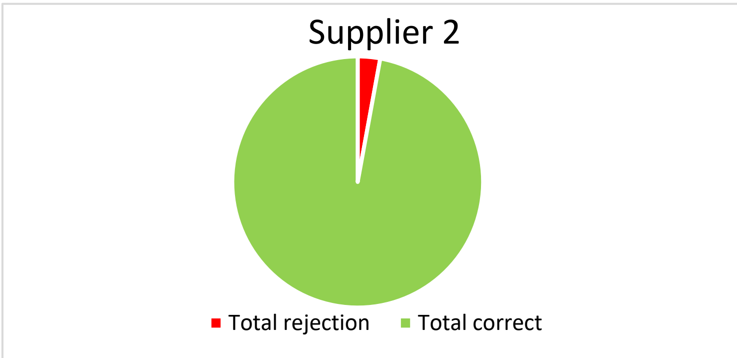


Figure 5-6: Overview of the performance of Supplier 2. Exact percentages removed due to confidentiality.

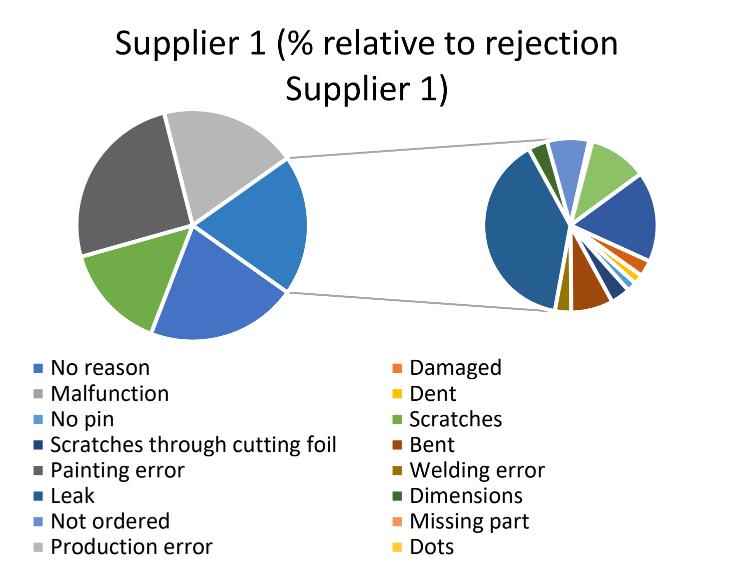


Figure 5-7: Overview of the reasons for rejection for Supplier 1. Exact percentages removed due to confidentiality.

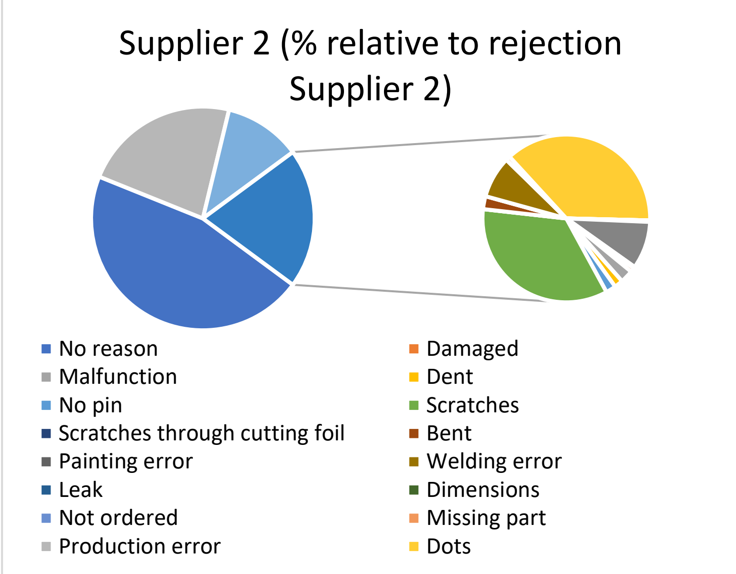


Figure 5-8: Overview of the reasons for rejection for Supplier 2. Exact percentages removed due to confidentiality.

5.5 Analysis of results

After the quality issues tool has been created, the results are analyzed. The following points stand out during analysis:

- **Overall performance**. General speaking, most of the products that are delivered are of good quality and are not rejected because of a quality issue. Most products do not have a rejection at all ([redacted] Table 14) or do have little rejections, while there are some products with a lot of rejections (see Figure 5-4). Moreover, [redacted] of the delivered components are rejected because of a quality issue. Comparing this with the percentage of orders containing a quality issue (22%), this percentage is relatively low. The rejection rate per product is also not extremely high: 90% of the components have a rejection rate below [redacted].
- **Performance of suppliers**. Only [redacted] of the components delivered by Supplier 1 contains a quality issue and [redacted] of the components delivered by Supplier 2 contains a quality issue (see Figures 5-4 and 5-5). As there are no formal agreements about the allowable rejection rate, it cannot be concluded if these are within the allowable range. However, these percentages are relatively low relative to the other errors but still seen as too high by stakeholders within ESS. Therefore, solutions are necessary to encounter fewer quality issues at the line (see next Chapter). Two notes must be made regarding this analysis. First, the quantity supplied by the other suppliers is relatively low. Therefore, the delivered quantities of these parties are not included. The rejections, however, are counted and used in the general calculated measures. No conclusions can be drawn about the performance of these suppliers. Second, Supplier 1 does also perform powder coating for other suppliers of ESS. This powder coating does often contain an issue and would, therefore, increase the rejection percentage of Supplier 1 heavily. This is, however, not visible in the percentage as agreements has been made that the original supplier is responsible for the component. Therefore, the rejection percentage of the other suppliers are influenced negatively and the percentage of Supplier 1 is not affected.
- **Data is sometimes not available**. Some components do not have data about rejections or data about the delivered quantities. The lack of data about the delivered quantities can have multiple reasons: (1) the supplier is not Supplier 1 or Supplier 2 (of which only the delivered quantities are included in the tool) or (2) the component is received before 23-04-19 (of which no data is included in the tool, see Appendix E). Due to this lack of data, some components do have (unrealistically) high rejection rates, as (large) quantities are received before this date. In the top fifteen components with highest rejection rates, for example, [redacted] components have a rejection rate of greater than (or equal to) 100%, which is in reality not possible.
- *Censored*

[redacted] *Censored*

- **Frequently occurring reasons over all components**. The most occurring reason in the data is “No reason”. As no reason is given for rejection, this makes analysis and follow-up actions difficult. Other than “No reason”, the top five frequently booked reasons are: (1) production error, (2) scratches, (3) paint error, (4) sharp angles and (5) dots. Just as “No reason”, it is not clear what the exact reason for the rejection is when production error is booked. Remarkable, however, that most of the rejections with this reason are only in six components (only considering the major suppliers Supplier 1 and Supplier 2). [redacted] This indicates that this is a frequently occurring reason for the components used in the [redacted] product style. Moreover, the third on the list, paint error, logically only occurs in components that have a color. Further remarkable is that most of the components with a paint error are delivered by [redacted]. All rejections of the fourth reason (sharp angles, [redacted] in total) are mentioned at only one component: [redacted]. This rejection rate of this component is, however, relatively low as this component is also delivered relatively frequent.
- **Frequently occurring reasons per component**. Besides the frequently occurring reasons over all components, a pattern can be seen per component (and per supplier): each component (supplier) has its own most-frequent mentioned reason for rejection and each component (supplier) does only have a small number of reasons for rejection. This indicates that certain issues occur more frequent than others and are component (supplier) specific.
- **The rejection rate for colored components is about the same as components without color**. Analyzing the rejection rate, no real difference in the rejection rate of colored and non-colored components can be discovered. Remarkable, however, is that the total number of components delivered and rejected is significantly lower than components without a color. This indicates that components without color are used more frequently in production and, therefore, more demanded by customers.

To ease future analyses, I advise to change certain points of the reporting and tracking of quality issues. The points I recommend looking at do not takes much time or effort to change but really help future analyses. I have identified the following improvement points:

- **Always mention a reason**. Adding always a reason ensures the rejection can be analyzed and the right follow-up actions can be taken.
- **Reason from standardized list**. The quality manager uses a standardized list only since last year and I recommend using this list consequently. Besides, I recommend making sure specify the reasons better, as production error does not say much about the kind of quality issue seen.
- **Add assembly line where components is (or should be) used**. Although this information can be deduced from the component name (only if one has knowledge of the components), it is easy when the assembly line is added. When added to the data, the information of a certain line can be extracted from all the data more easily. Besides, the tool can then be adapted to filter out a line automatically. When reporting a quality issue via the ERP system, the correct line is automatically recorded with the quality issue. In the manual recording of the quality manager, however, this is missing.
- **Add discovery place in production facility**. By adding the discovery place (the place where the quality issue is identified, from a standardized list), an analysis can be made about the proportion of the quality issues identified at the goods receipt relative to other places in the production. Specific interventions can be introduced and tested more easily when the discovery place is known.

5.6 Conclusion

This chapter described the tool that has been made in Excel using VBA to provide insights in the quality issues related to the container-series line. The tool is able to provide and visualize the quality rejections both per component and over all components used at the container-series line. Based on the results, the conclusions regarding the performance (both overall and per supplier) have been drawn. Besides, conclusions regarding data, [redacted] , frequently occurring reasons and colored components have been drawn. Moreover, some recommendations regarding future analysis have been proposed.

6. Encountering fewer quality issues at the line

This chapter provides information regarding the process of finding solutions to encounter fewer quality issues on the container-series line. Section 6.1 introduces the approach to the reader. The knowledge gathered from literature is provided in Section 6.2. Next, the solution design is provided, containing the rationale of the solutions, criteria of the solutions, list of possible solutions and selection of solutions. The selected solutions are described more detailed in Section 6.4. An implementation plan for the six selected solutions has been constructed and is provided in Section 6.5. Lastly, Section 6.6 provides the conclusions of this chapter.

6.1 Approach

The aim is to find solutions to improve the guarantee of good quality components on the line and, with that, lower the percentage of orders with a quality issue. Reducing the number of quality issues has a high priority, as these cost time and decrease the production capacity of the line. To come up with solutions, first literature about quality is analyzed. Moreover, criteria will be identified which the solutions must possess in order to be a good solution for the goods receipt process. These criteria will be identified by observing the process and speaking with the stakeholders. Subsequently, solutions will be identified by doing observations and organizing a brainstorm session. These solutions are assessed on the identified criteria. Based on the assessment, a set of solutions will be selected. This set of solutions will be worked out more detailed in an implementation plan.

6.2 Literature

To be able to come up with solutions and process the solutions correctly, a literature search has been performed. Two interesting theories for solutions have been identified: Total Quality Management and Supplier Quality Management. These theories are described shortly below. Lastly, knowledge about implementation plans and change management is needed and described shortly below.

6.2.1 Total Quality Management

Total Quality Management (TQM) is a set of approaches that emphasize the need for quality in the complete organization (Kiran, 2017; Slack et al., 2016). Many more definitions are available for TQM, but they all stress the idea of integrating quality in all parts within an organization. TQM stresses the importance of continuous improvement in the quality improvements of companies (Mehra & Ranganathan, 2008).

Another aspect of TQM is the conformance of the product or service to the needs of the customer (Reed et al., 2000; Slack et al., 2016). If the needs and expectations of customers are met, customers are satisfied, return to the company and increase the competitive advantage of a company (Agus & Hassan, 2011; Mehra & Ranganathan, 2008). Therefore, the customer defines the quality objectives. These quality objectives can be used to increase the quality during the complete process.

TQM accounts for all costs related to quality must be considered. These “quality cost” can be categorized in four different categories (Albright & Roth, 1992; Slack et al., 2016):

- **Prevention costs**. Costs incurred to prevent producing a non-conform product/service or error;
- **Appraisal costs**. Costs incurred in checking and identifying a non-conform product/service before, during and after the creation;
- **Internal failure costs**. Costs incurred by solving problems that have occurred internally due to (quality) errors;
- **External failure costs**. Costs incurred by solving problems that have occurred externally due to (quality) errors.

According to the traditional model of costs, a company can reduce the quality cost drastically by investing both money and effort in appraisal and prevention (Albright & Roth, 1992; Slack et al., 2016). In other words, actions must be taken to make sure quality issues do not occur at all (“get it right first time”, Slack et al. (2016)) and quality issues are not affected other parties, both internal and external.

6.2.2 Supplier Quality Management & Development

Supplier Quality Management (SQM) or Supplier Quality Development (SQD) is “a set of activities in most cases initiated by the management to improve organizational performance” (Jagtap et al., 2017, p. 1). Typical activities of SQM include measuring and tracking the performance of suppliers and establishing contact channels with all suppliers. These, in turn, can be used to assess the performance of the supplier and to take the right follow-up actions (Jagtap et al., 2017; Noshad & Awasthi, 2015; Sang Chin et al., 2006).

To increase the performance of suppliers, many activities can be taken by a manufacturer (Jagtap et al., 2017; Noshad & Awasthi, 2015). These activities depend on the type of performance of a supplier a manufacturer wants to increase. Among others, the activities can consist of introducing competition, capture expectations, promise future benefits and perform trainings (Monczka et al., 1993, as cited in Jagtap et al., 2017).

According to Lee & Li (2018), a manufacturer can improve the quality of its sourced products by using one (or a combination of) the following three methods:

- **Inspection**. Inspection is seen as the traditional method to improve quality and has two main benefits: (1) issues are discovered when delivered and do not reach end customers (which cost both money and time) and (2) suppliers can be held responsible more easily (Lee & Li, 2018).
- **Investments**. By providing support, knowledge and/or money to the production process of suppliers, costs can be reduced and quality can be improved (Lee & Li, 2018). As the costs decrease and quality improves, the manufacturer is influenced indirectly by the success. Especially for suppliers in developing countries, investments may be needed to improve the quality of the supplier as knowledge about quality standards and managing methods may be lacking (Lee & Li, 2018).
- **Incentives**. As efforts of suppliers are necessary to increase/ensure quality and these efforts are both difficult to measure and not contractible, no or little efforts will be made. By giving suppliers incentives to deliver consistent higher quality (by, for example, providing economic incentives), the motivation to make quality efforts can be increased (Lee & Li, 2018).

6.2.3 Implementation plans and change management

Heerkens and van Winden (2017) identify two main principles important in an implementation plan: (1) the technical side and (2) the social side. The technical side describes all the activities that need to be planned and executed. Important here is to provide this step-by-step, to make implementation as simple as possible. The social side of the implementation plan describes the roles and responsibilities of individuals during the implementation process. In addition, it should be described how to get all individuals on board with the change specific. Besides these two principles, Heerkens and van Winden (2017) also emphasize the importance of stating the goal, costs, responsibilities and tracking of progress per measure.

According to Galli (2018, p. 124), change management is “the application of a structured process and set of tools for leading the people side of change to achieve a desired business outcome”. To effectively implement a solution, the need for change from the current situation to the desired situation must be stressed and clear for the involved parties. General speaking, there are five steps in each change management processes (Galli, 2018): (1) identify the need for change, (2) change details, (3) approach, (4) implementation and (5) monitoring. Galli (2018) continues with an analysis of various change management models and concludes the following: “no matter the model, change will only be successful if communicated and accepted by employees or project team members”(Galli, 2018, p. 129).

6.3 Solutions design

This section contains the design of the solutions. Section 6.3.1 describes the rationale of the solutions. Next, Section 6.3.2 describes the criteria the solutions must meet. The solution alternatives can be read in Section 6.3.3. Lastly, Section 6.3.4 contains an analysis and selection of solutions for elaboration in an implementation plan.

6.3.1 Rationale of solutions

When a component needs to be rejected at the goods receipt and the quality issue is not a consequence of an action of ESS, the supplier is contacted for a solution (either replacements or restitution). Because these quality issues are discovered before using it in production, the production planner can anticipate on these issues and reschedule orders when necessary. This way, no real interruptions of the assembly process are caused.

When a quality issue is discovered at the line, however, greater interruptions occur. First, the issue must be reported in the tablet and the right solution is determined by the production leader and planner. Because these parties need to find a solution for these issues (either decrease production quantity or picking of new components) by discussing it with other stakeholders, the assembly process is affected. Although the workers on the line continue with the current or another order, some time is lost by handling the quality issue. Because this takes extra time, time is wasted which could be spent on assembling items (and thus lowers the production capacity). This can be linked to lean management, which is a management theory that tries to avoid and reduce waste (muda) and other non-value added activities (Teich & Faddoul, 2013).

Thus, quality issues that are discovered at the line result in more costs and variability in production time (cycle times) than quality issues discovered at the goods receipt. Therefore, more quality issues should be discovered and filtered earlier in the process. This means that suppliers need to deliver less components with quality issues or the quality issue must be filtered out before arriving at the line (for example at goods receipt or picking).

Relating this idea to the cost of quality from TQM, this improvement can cost extra money for ESS (prevention cost) because time and tools can be needed or the procedure can take longer. This decrease in other costs are not specified further in this thesis as the main focus is to reduce the time wasted on quality issues and use these to produce more products. Another point of TQM that is worth mentioning is the idea of putting quality on the agenda of all stakeholders. By stressing the importance of quality in all departments within ESS, quality can be a joint responsibility of all departments.

6.3.2 Criteria of the solution

To ensure the proposed solutions work, the following criteria are identified which a solution must possess to be a solution that works in practice. The criteria are based on observations, own assessment and interviews with workers of the goods receipt. The following criteria are identified:

- **Efficient**. As there is much work and limited workers available, the solution must not take too much time. The proposed solutions must, therefore, be designed properly to take equal (or less) time than the current process.
- **Practical**. The solution must not only work theoretical, but also in practice. Therefore, the solution must be practical, which means that a worker must be able to work with the solution in an easy way and no comprehensive actions must be necessary.
- **User-friendliness**. This factor can be seen as a part of the former criteria but is different in the sense that the focus of this criteria is that the solution must be designed in such a way that it is always clear how it works and that it is easy to apply. When external tools are necessary, these must also be designed user-friendly in order to make the process as smooth as possible for the workers at the goods receipt.
- **Costs**. Costs are important for the solution. If a very good solution is proposed that drastically improves the performance but requires a large investment, the solution is not feasible. The proposed solution, however, does also not need to be free of charge. What is important is that the investment needed is proportional to the expected issues it solves.

6.3.3 Solution alternatives

To come up with solutions, a brainstorm session has been organized with stakeholders of the processes: leader of the goods receipt, quality manager, purchasing manager and a member from the R&D department.

The brainstorm session started with a small recap of the research topic and the rationale of the solution. Next, some results from the quality issues tool were shown and discussed, to ensure the participants have the latest knowledge regarding the frequently occurring quality issues. Afterwards, the actual brainstorm and discussion began, resulting in many possible solutions.

Besides the solutions from the brainstorm session, some own solutions have been identified. These solutions are identified during working at the different stations at the process, interviewing stakeholders and doing observations in the production facility. Moreover, ideas from TQM and SQM/SQD are incorporated. Especially the idea of emphasizing quality throughout the complete organization and, thus, stressing the role of other parties than line 5 is integrated in the solutions.

Combining the solutions from the brainstorm session, own solutions and theory of TQM and SQM/SQD, in total twelve solutions have been identified, which are depicted in Figure 6-1. A short description per solution is provided in Appendix F.1.

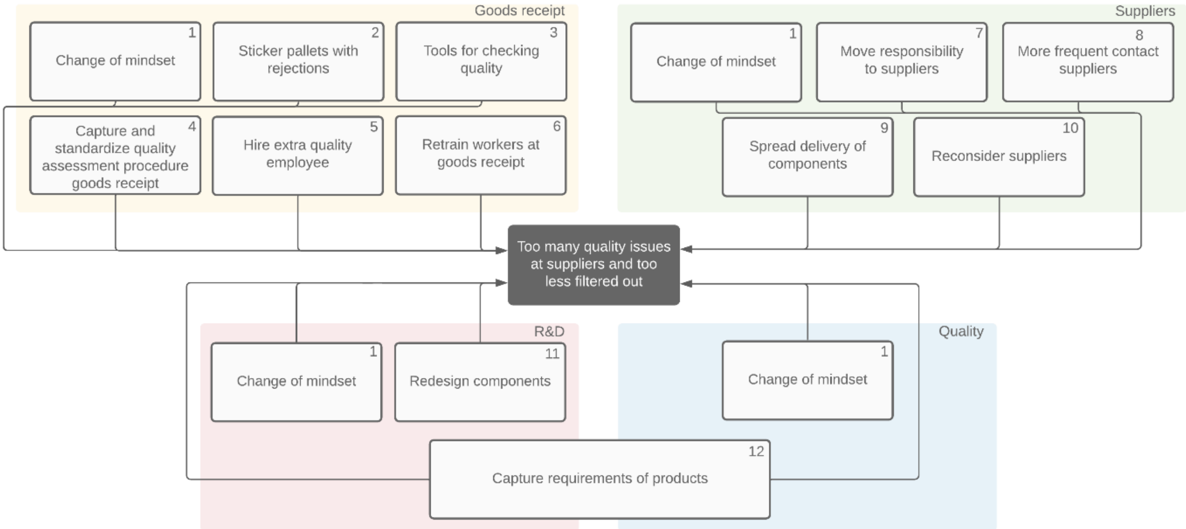


Figure 6-1: Overview of the solutions to encounter fewer quality issues at the line, sorted per discipline.

6.3.4 Analysis and selection of solutions

All of the identified solutions in the previous section are potential good solutions and conform the criteria of Section 6.3.2. To select solutions to work out more detailed in an implementation plan, further analysis of the solutions are necessary. To enhance analysis, the solutions are sorted per discipline (see Figure 6-1): goods receipt, suppliers, R&D and quality.

All solutions fit to one discipline, with the exception of two solutions: number one and twelve. The reason for this is that the mindset of quality (solution number one) must be implemented throughout the company and suppliers (relating the idea of TQM). Therefore, this idea does not belong to one single discipline. Solution twelve does also not fit to one single discipline but actually is a combined responsibility of two disciplines: the R&D and quality. It is only with combined effort possible to capture and make all requirements measurable. Therefore, this solution is assigned to both disciplines.

Further analyzing the solutions, a difference in time horizon between the solutions can be identified. Some solutions are possible to be implemented in the short-term while others only on the long-term. Moreover, some solutions can only be implemented after some other solutions are implemented as these are dependent on (the result of) each other. This difference in time and sequence is captured by dividing the ideas over four time horizons (see Figure 6-2): short-term (weeks), medium-term (months), long-term (1-2 years) and very long-term (2+ years). One can work on and implement solutions from a next time window if (almost) all solutions of the previous window are implemented.

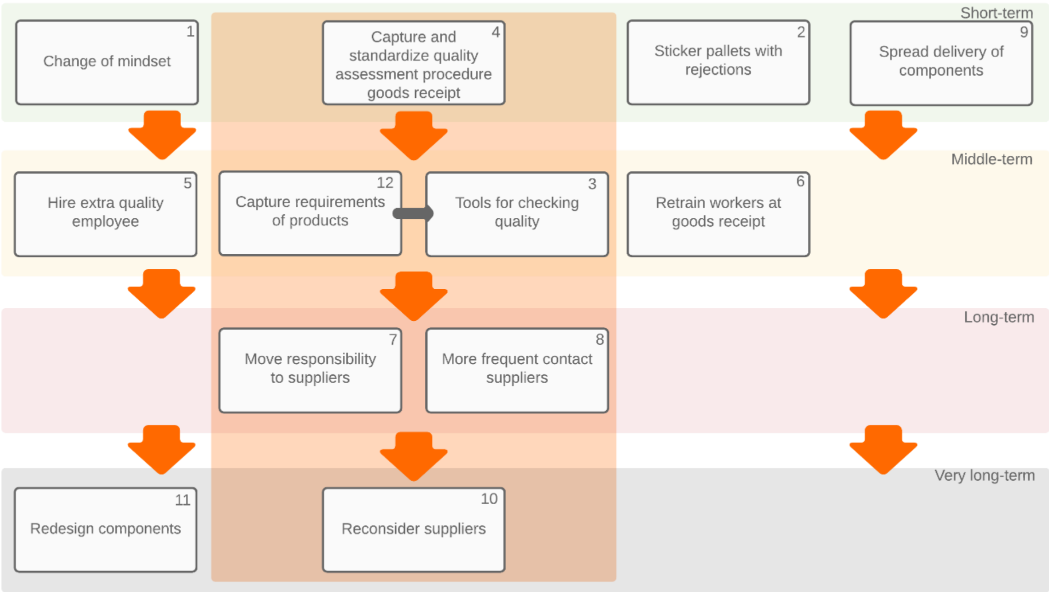


Figure 6-2: Overview of the solutions to encounter fewer quality issues at the line, sorted per time window.

Using the solutions sorted on time window, it is striking that some solutions are very interconnected and can only be implemented in a certain sequence. This sequence is marked orange in Figure 6-2 and contains the following solutions (from short-term to long-term):

4. Capture and standardize quality assessment procedure of the goods receipt;
5. Capture requirements of components/products;
6. Tools for checking quality (only after solution 2);
4. Move more responsibility to suppliers;
5. More frequent contact with suppliers;
6. Reconsider and change suppliers.

Analyzing the possible solutions, it is believed that the combination of these solutions will have the most impact against the lowest costs. Therefore, these solutions will be described and worked out more detailed in an implementation plan. As the solutions of the larger time windows can only be worked out and implemented fully if the solution of the lower time windows are fully implemented, the solution of the lower windows will be described most extensively. For the solutions in the larger time windows, ideas and theories will be given but these will not be applied or worked out further.

This does not mean, however, that the other identified solutions are no good solutions. The other solutions are as good as the other solutions in the sense that these lower the quality rejections seen at the line but these are not as connected to other solutions as the six solutions mentioned above. Besides, it is expected that these individual solutions will have less impact compared with the six solutions. Therefore, the other solutions are not worked out more detailed here. However, I do recommend ESS to consider, investigate and implement (some of) these other solutions too.

6.4 Selected solutions

This section treats the selected solutions in more detail. In each of the subsections below, a solution is described more detailed including interesting theories and concepts.

6.4.1 Capture and standardize quality assessment procedure of the goods receipt

To filter out more quality issues at the goods receipt, the current unstandardized procedure can be changed to a fixed, data-driven procedure in which the sample size is pre-determined. With the help of historical rejection data, the sample size and special points of attention could be determined. In the ideal situation, these could be shown in the scanner after scanning the barcode of the component. To speed up implementation, both can be shown in the beginning in a simple Excel tool.

To ease implementation, a draft version of the determination of the sample size and attention points is made. Based on historical rejection percentage, the component can fall in different categories (see Table 16). A delivery can be per pallet (containing multiple boxes) and per tobacco box ("tabaksdoos"). Per subgroup, the sample size is determined and fixed. For delivery per pallet, the number of boxes per pallet and the number of components per box is determined. For delivery per tobacco box, only the number of components checked is determined. The numbers in Table 16 are based on an own analysis of historical data and verified with the quality manager. The exact values, however, must be determined and tweaked in practice.

Based on the frequency of certain reasons for rejection, special attention points could be identified. The special attention points could be considered and checked more thoroughly in the quality assessment. For these points, a threshold value of 20% could be used, meaning that reasons that occur in more than 20% of the rejections of a component are marked as attention points.

Table 16: Overview of an example of the distribution of groups and sample size of each group.

Category	Begin rejection percentage	End rejection percentage	Per pallet	Per box	Per tobacco box
1.	0.0%	9.9%	1	3	5
2.	10.0%	19.9%	2	5	8
3.	20.0%	49.9%	4	8	10
4.	50.0%	∞	Everything	Everything	Everything

Besides the sample size and attention point, a fixed order of quality criteria could be useful. To make the fixed process as easy as possible, quality criteria ranging from general criteria to more specific ones are proposed. These criteria are based on interviews, practical considerations and own experiences in the goods receipt. The following criteria are identified and must be checked separately: dimensions, straightness, edges, color & look, surfaces (including scratches, stains, dots, etc.) and other points (possibly coming from identified attention points). When using a standardized and fixed sequence of check criteria, all applicable and important criteria are checked with certainty and not omitted.

When an issue is discovered, the sample size must be increased. As fixed a rule of thumb, an extra box per layer (in case of a pallet) or five additional components (in case of tobacco box) can be checked extra. A difficulty, however, is that no clear distinction can be made between issues that are minor issues (that still can be used in the product) and issues that are not (and, thus, must be rejected). The reason for this is that no requirements for the components are captured yet. Therefore, this consideration is still based on the experience of the goods receipt worker. When the requirements are captured, these can be added in the procedure.

A final note has to be placed about the new process of the goods receipt. The quantity determination in the new process can be the same as the current counting principle. However, I recommend investigating the feasibility of a weighting principle to check the quantity of bulk components.

6.4.2 Capture requirements of products

This solution is probably the most important recommendation of all selected solutions. For all parties in the process, the quality requirements of components and products are unclear. Therefore, components with bad quality are delivered and not filtered out before arriving at the line. This solution consists of two components: (1) the actual requirements of the components and (2) the deviation in the requirements that are allowed.

For each component, correct drawings must be made and available for all parties. These drawings must include the requirements and tolerances in terms of dimensions, straightness, sharpness of surfaces, welds (type) and color (color code including the thickness of the paint). Other details and particularities, such as surfaces that must be free of coating, must also be indicated here.

Besides the exact requirements, it must be clear which deviations in the requirements are allowed and which are not. A surface, for example, may be barely or not visible in the final product and, therefore, may contain some scratches. For these deviations, the idea of the "Zichtvlak categoriseringsnorm" ("Visual area categorization standard") initiated by the quality manager and the R&D department can be applied on a greater scale to all components.

The idea of the visual area categorization standard is to capture the allowable deviations in the components and the circumstances under which the inspection must take place (eye distance, light type). In the visual area categorization standard, all surfaces of a product are divided in four different categories, based on visibility during normal use of the final product. For both coated and uncoated, a couple of requirements including acceptability are defined. The acceptability of certain defects are different for the four categories. The strictest requirements of acceptability are for the primary sight surfaces, the least strict requirements for the hidden sight surfaces.

The visual area categorization standard is a good method to capture the allowable deviation in the requirements. Therefore, I recommend applying this method on a big scale and divide each surface of the products used on the container-series line in the four categories described above. The greatest effect will be achieved by starting with products that have a relative high rejection rate or are hard to assess on quality. For new products, this could be standard in the development process.

When the requirements and allowable deviations in requirements are communicated in advance, all involved parties can anticipate on these. The suppliers know precisely what the requirements are of the components they need to deliver and when a component will be rejected. There will be no discussions about the delivery agreements and on the rejection due to poor quality. For the workers at the goods receipt, it is clear what the standards are and when a component needs to be rejected. No more hesitations will be about the quality of a component and, as a consequence, more components can be assessed more properly. Components, for which there are now doubts and thus not rejected while these are rejected at the line, can be filtered out and rejected already at the goods receipt.

Besides, the pickers can be trained to also work with this system and can assess the quality of the component themselves when picking. This way, the pickers do not need to just pick the component from which it is already known it will be rejected. Consequently, these components do not arrive at the line with all its bad consequences. Lastly, it is for the workers on the line clearer which components need to be rejected, which can save time (especially when there are hesitations about the quality).

6.4.3 Tools for checking quality

To make the checking of quality both easier and more objective, quality tools can be useful. Especially in the combination of clear requirements and quality issues allowed (see above), certain tools can help to speed up and increase the accuracy of the quality assessment at the goods receipt. I identified the following tools that could be useful in assessing the quality:

- **Color chart**. To determine if the component has the correct color, a color chart can be used containing all possible colors in which the components can be ordered (and including allowable deviations). From the requirements of the component, the correct color code can be gathered. This color code can be found on the color chart and positioned along the product. A visual comparison can be made between the color it should be (from the color chart) and the color it actually is. If the color corresponds with the color on the chart or is within the deviations (as also on the chart), the color of the component is correct.
- **Thickness meter**. The thickness of the coating can be determined with the help of a coating thickness meter. The thickness meter can be placed on a coated surface and indicates the thickness of the coating. As this process takes some time and not many problems are currently faced with the thickness, a thickness meter can only be used when there are hesitations regarding the thickness of the coating.

- **Spirit level**. Straightness is currently determined using the eye or by placing the component on a straight surface. Using a spirit level, the straightness can be determined both quickly and more objectively. Different sizes of spirit levels could be useful for different components.
- **Blocks or pins for critical points**. Critical points are those points of a part that must have certain dimensions with certainty as otherwise the component does not fit properly with other components. As these critical points are important for the functioning of the product, it is important to check the dimensions of these. To check the dimensions of these points quickly and easily, special blocks or pins can be introduced. These blocks or pins have the correct dimensions of the component that must fit with or in the critical point. When blocks or pins fit properly, the dimensions of the critical point are correct.
- **Scratches tool**. Instead of manually measuring the size of a scratch, a special tool can be developed and used. To easily measure if a scratch is allowed or not, scratches can be divided into categories based on their size, for example in four categories: small, medium, large, extremely large. By designing a special ruler consisting of these categories in the form of colored transparent blocks (see Figure 6-2), it can easily be determined in which category the scratches fall by placing the tool on the scratch. This category can be compared with the maximum allowable category of scratches on the surface (based on the allowable deviations). Based on this comparison, it can be easily determined if a component must be rejected or not.

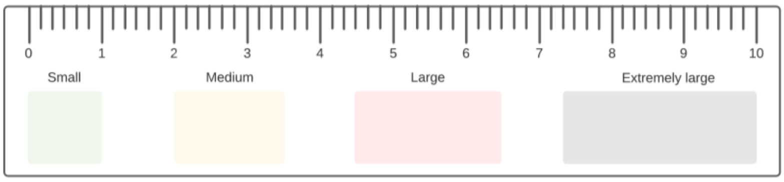


Figure 6-3: Example of tool that can be developed to measure scratches easier (not on scale).

6.4.4 Move responsibility to suppliers

In the long-term, the responsibility of delivering good quality components can be moved to the suppliers. This means that suppliers will be accounted for 100% of the consequences caused by the quality issue, in the form of a penalty. This penalty should represent all the costs and time spent on the quality issue. When accountable for both time and costs, the idea is that an incentive is created for the supplier to perform better as it costs more to deliver components with bad quality.

This solution, however, only works if clear arrangements have been made regarding the concept quality and the size of the penalty. When the requirements and allowable deviations are clear, these must be communicated with the suppliers. Only when these are communicated and time has been given to adapt to these new requirements, the responsibility can be fully moved. Besides, the size of the penalty should be agreed upon beforehand, making it as clear as possible for the supplier.

6.4.5 More frequent contact with suppliers

More frequent contact with the suppliers can help with detecting and solving problems with the quality of delivered components more quickly. During a meeting with the supplier, the performance of the previous period can be discussed in terms of items delivered and quality issues seen. This is already part of the current meetings but this aspect must be made important. The quality issues can be discussed and the right actions can be taken to resolve these. This meeting should take place frequently, for example once a quarter.

Besides the performance, contact does also mean visiting the suppliers' plants and showing the own plant. When more insight is created in the processes of each other, both parties will understand each other better. Certain issues seen at ESS can be related to the production process of the supplier more easily. A supplier could better understand why quality issues are a problem and can anticipate on this.

6.4.6 Reconsider and change suppliers

When certain suppliers do structurally deliver components with bad quality and there is no increase in performance to be expected, it could be good to reconsider certain suppliers. Maybe there exists a supplier at comparable (or slightly higher) costs, but which is able to deliver high-quality components. As first suppliers must know the exact requirements of the components, need time to adapt to these changes and then be judged on the performance, this idea can only be applied on the very long-term.

To judge the performance of suppliers, a dashboard could be developed containing the most important measures and Key Performance Indicators (KPIs) for comparison. Based on these KPIs, the performance of the supplier can be determined and certain follow-up actions can be identified. To be able to judge the performance of a supplier well, the KPIs should cover all important aspects of the performance. One of the most important subjects is the quality of the delivered components. Examples of subjects that can be placed in the dashboard are delivery, responsiveness, quality and price/costs.

6.5 Implementation plan

This section describes the implementation plan made for the chosen solutions and is based on the literature found on implementation plans and change management (Section 6.2.3). First, the current state and need for change are described. Subsequently, the implementation is described from both a technical and social side. Next, the measures to monitor the solutions are described. Lastly, the costs and benefits and increase in production capacity is discussed.

6.5.1 Current state and need for change

Currently, 22% of the orders assembled on the containers-series line contain a quality issue. The quality issues discovered on the line lead to high costs, large variability in production time (cycle times) and lower capacity of the line. To increase the capacity of the line and cut costs, more quality issues must be filtered out beforehand.

The current goods receipt process is not structured or standardized and it is not clear how much needs to be checked (see Section 2.3). A random number of products is checked on quality, without fixed quality criteria and, therefore, certain criteria in the quality check can be forgotten easily. Based on the experience of the goods receipt workers, the workers know which issues occur frequently. However, the workers do not know these frequently occurring issues of all components because of the large number of components seen by the workers and the arrival of new components.

Besides the non-standardized process, it is not clear which quality issues are inside the norm and which are not. The requirements are not captured yet, making it unclear for all parties if a component is of good quality or if it must be rejected. Besides, the quality criteria cannot be measured objectively with the help of tools. The only tool used to help determine the quality of components is measuring tape, to help measuring the dimensions of the components. Instead of measuring objectively, the judgement of quality is currently based on the experience of the workers at the goods receipt. When hesitating, components are marked and booked in as good quality components. Only when it is sure a quality issue is a problem, components are rejected. Moreover, the pickers are currently not allowed to reject a component because of a quality issue and must just pick the component. Therefore, a situation can occur in which the pickers need to pick a component and are sure that the component will be rejected at the line, resulting in extra wasted time and costs.

In addition, too many components are delivered with a quality issue by the suppliers. There is no sense of complete and full responsibility for delivering components without an error and, consequently, bad components are delivered. As many components arrive at ESS, not all components can be checked and issues will only be seen when arriving at the line.

Moreover, the contact with suppliers is too infrequent. Currently, an assessment meeting with suppliers is planned once a year before Christmas. As there is no frequent contact, it is not fully known which issues currently occur and no quick actions can be taken to resolve these issues. Besides the infrequent contact, the assessment of the performance is also too infrequent and the right actions are not taken. Suppliers are often chosen based on historical reasons and not on performance measures.

6.5.2 Technical side

A description of the solutions, including interesting theories and concepts, is provided in the previous section (Section 6.4). This section focuses on the steps necessary for each solution. Figure 6-4 provides an overview of the global steps that are necessary for the implementation of each solution. Responsibilities are not listed in this figure, as these are treated in the social side (next subsection).

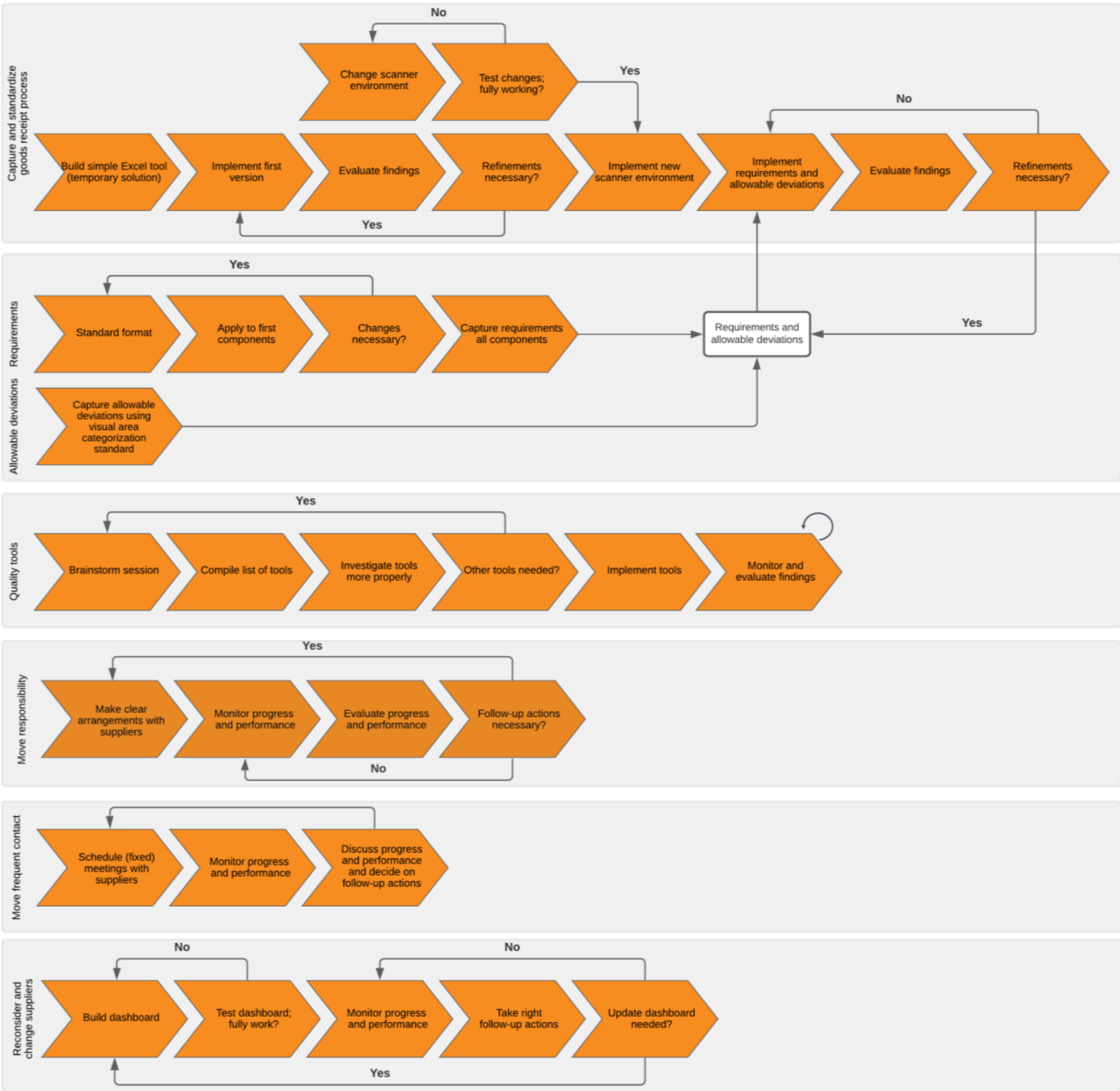


Figure 6-4: Overview of the global steps that are necessary to implement the solutions.

6.5.3 Social side

To ease implementation, a rough planning and a division of responsibilities have been made. Table 17 shows this planning and overview of responsibilities. The legend shown in Table 18 provides an explanation of the colors used in the planning. The planning made here can be started every month and does not necessarily have to start at the beginning of a new year. The planning is made for the first 2.5 years but the last 3 solutions continue after these 2.5 years. The time period are based on own estimations and verified with the quality manager. A more detailed explanation of the collaborations, starting times and activities is provided in Appendix F.2.

Table 17: Overview of the planning and responsibility for the solutions. Colours correspond with colours from legend (see Table 18).

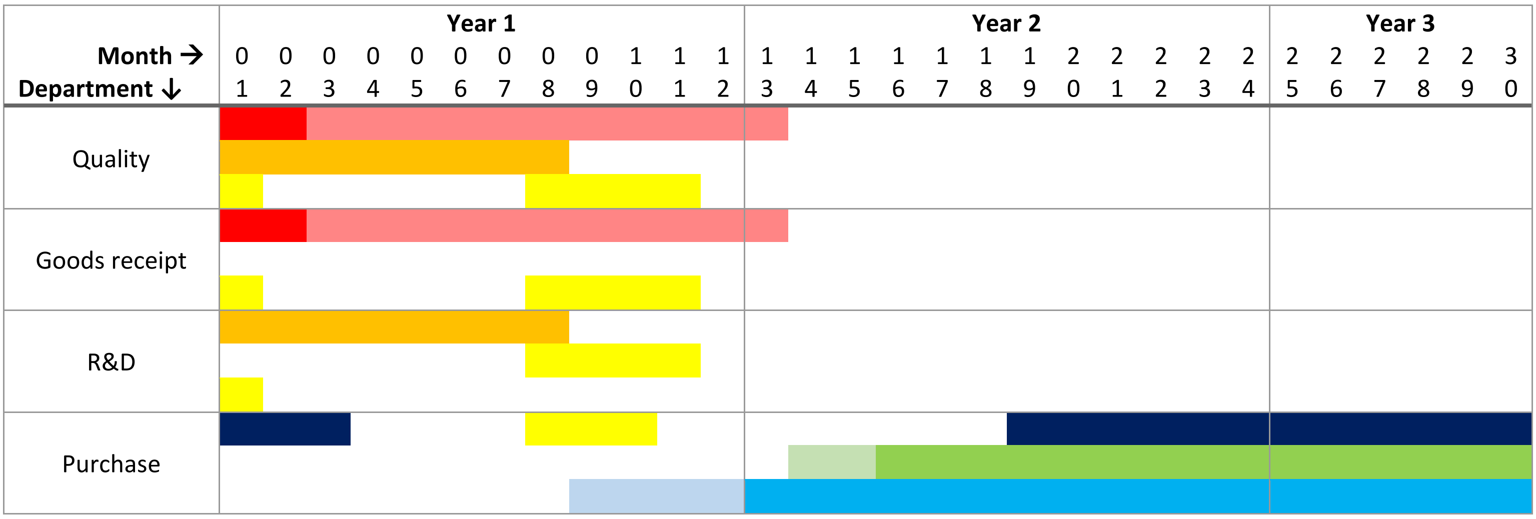


Table 18: Legend of the planning, each colour corresponding with a solution.

Solution	Colour
1. Capture and standardize quality assessment procedure goods receipt	
2. Capture requirements of components / products	
3. Tools for checking quality	
4. Move responsibility more to suppliers	
5. More frequent contact with	
6. Reconsider suppliers	

6.5.4 Evaluating

Based on certain quality-related Key Performance Indicators (KPIs), the progress towards the goal of lowering the percentage of orders that contain a quality issue from 22% to 17% can be measured. To measure the effect of the solutions, some quality KPIs are identified. Every solution focuses on a different part in or outside the company. Therefore, to judge whether a certain solution works, specific KPIs focusing on the effect of the solution are also identified.

To measure the effect of the solutions, the following KPIs have been identified:

- Percentage of orders containing quality issues;
- Ratio quality issues as a consequence of ESS relative to consequence of suppliers;
- Average number of quality issues per order with a quality issue;
- Ratio of quality issues discovered on the line relative to discovered at the goods receipt;

6.5.5 Costs, benefits and production capacity

To determine if the solutions are worth implementing, the costs and benefits must be weighted and potential increase in production capacity. As the solutions all have a different timing of implementation (see planning above) and, therefore, the effect will slightly decrease every year, the expected costs and benefits are calculated for the first three year separately. The next subsections treat respectively the benefits, costs, results of the costs-benefit analysis and potential increase in production capacity.

Costs

Table 19 on the next page contains an overview of the costs related to the implementation of the solutions. To quantify the costs, first important components of each solution are identified and an estimated duration is given (when applicable). With the help of the duration, the costs are estimated for all components corresponding with the planning identified in the previous subsection. For components that require some time of a (non-production) employee, a fixed hourly salary is taken of €30.00 (see Appendix F.3). Other important assumptions made to quantify these costs have been summarized in Appendix F.3. For all components that do not have a duration and employee, the costs are based on findings identified during interviews. To verify the durations and costs, the durations and costs are presented to the quality manager. Some small adaptions have been made after this presentation.

Adding up all costs of the components of the solutions, the costs per year for the next three years are found. Table 19 depicts the costs of the next three years. Remarkable is that the costs for the first year is much higher than the costs for the next three years. Reason for this is that some initial (and relatively large) investments are needed for the solutions. When these investments have been made, only small continuous investments are needed (mostly time of some employees).

Table 19: Overview of the costs for the next three years when implementing the six solutions.

Solution	Components	Duration		Year 1	Year 2	Year 3	One-off costs
1. Capture and standardize quality assessment procedure goods receipt	Implementation	90	min	€ 45.00	X	X	✔
	Evaluation	10	min per day first two months	€ 187.50[1]	X	X	✔
	Changing scanner environment	X		€ 50.00	X	X	✔
	Refinements and implement requirements	120	min per month	€ 2,250.00[2]	€ 60.00	X	✔
2. Capture requirements of components	Quality manager	4	hours per week	€ 3,600.00[3]	X	X	✔
	R&D employee	4	hours per week	€ 3,600.00[3]	X	X	✔
3. Tools for checking quality	Brainstorm session	2	Hours per department (3 in total)	€ 180.00	X	X	✔
	Investigate and choose tools	15	Hours	€ 450.00			
	Colour chart	X		€ 350.00	X	X	✔
	Spirit levels	X		€ 210.00	X	X	✔
	Blocks or pins for critical points	X		€ 130.00	X	X	✔
	Scratches tool	X		€ 300.00	X	X	✔
	Implementation	6	Hours	€ 180.00	X	X	✔
4. Move responsibility more to suppliers	Make clear agreements with suppliers	90	min per supplier	X	€ 315.00 [4]	X	✔
5. More frequent contact with	1.5 hours meeting every quarter	90	min per quarter per supplier	X	€ 945.00[5]	€ 1,260.00[6]	✘
6. Reconsider suppliers	Build + update dashboard	X		€ 500.00	€ 200.00	€ 100.00	✔ / ✘
	Monitor performance and determine follow up actions	90	min per week	X	€ 1,012.50[7]	€ 2,025.00[8]	✘
Total				€ 12,032.50	€ 2,532.50	€ 3,385.00	

[1] 10/60 × (45 working weeks ÷ 12 months × 2 months) × 5 days per week × €30.00
[2] 2 hours × (45 working weeks ÷ 12 months × 10 months) × €30.00
[3] 4 hours × (45 working weeks ÷ 12 months × 8 months) × €30.00
[4] 1 hour × 7 suppliers × €30.00
[5] 1.5 hours × 3 quarters × 7 suppliers × €30.00
[6] 1.5 hours × 4 quarters × 7 suppliers × €30.00
[7] 1.5 hours × (45 working weeks ÷ 2) × €30.00
[8] 1.5 hours × 45 working weeks × €30.00

Benefits

An overview of the costs per order with a quality issue is provided in Table 20. When the solutions work, the number of orders with a quality issue will decrease. Therefore, less costs are incurred to handle an order with a quality issue. As these costs can be saved due to the solutions, these costs are the benefits of the solutions.

The components and durations in Table 20 are based on observations and an interview with the quality manager. These components are translated to costs with the help of a standard hourly salary, with a difference between non-production employees (€30.00) and production employees (€24.08, see Appendix F.3). Other important assumptions can be found in Appendix F.3 as well.

Table 20: Overview of the benefits for the next three years when implementing the six solutions.

Cost caused by quality issue	Time (min)	Costs
Quality assessment. contact supplier. fix transporting and book quality issue by quality manager	30 – 120	€ 50.00[9]
Disturbance production	28	€ 0.38
Booking of quality issue in tablet;	1.5	€ 2.50
Internal supplier transporting rejected component	10	€ 0.25
Communicating problem with production leader;	1	€ 5.00
Determining solution by production leader and production planner;	5	€ 2.50
Picking of new components;	10	€ 0.12
Reinspection new components;	0.5	€ 0.38
Total	89	€ 60.75

Adding up the costs of all components, the costs per order with a quality issue are € 60.75. To compare the costs and benefits, the benefits must also be expressed per year. To make this comparison, the (expected) orders per year, both in total and with a quality issue, average number of quality issues per order and the expected decrease in the percentage of orders that contain a quality issue must be estimated and is provided in Table 21. Assumptions made to arrive at the numbers in Table 21 can be seen in Appendix F.3. Using the difference between the expected number of orders with quality issues when no action is taken and when the solutions are implemented, the benefits could be expressed as cost savings per year.

Table 21: Overview of the calculation of benefits for the next three years when implementing the six solutions.

	Year 1		Year 2		Year 3	
Total	100%	Censored	105%	Censored	115%	Censored
Expected (no action)	22%		22%		22%	
To	20%		18.5%		17%	
Difference	2%		3.5%		5%	
Quality issues per order			2.2			
Benefits	[redacted]					
Cost	€ 12,032.50		€ 2,532.50		€ 3,385.00	
Result	[redacted]					

Results cost-benefit analysis

Using the benefits and the costs identified above, the result per year can be calculated. Table 21 depicts this calculation. In the first year, the costs are greater than the expected benefits. Reason for. this is the high costs incurred in this year due to initial investments for solutions that must be made. However, this negative result is nullified by the positive results in year two and three. Overall, it is expected that about €19,000 can be saved in three years when implementing the solutions.

[9] Guideline Hansgrohe

Potential increase production capacity

Besides the costs that can be saved due to quality issues, the additional time can be used to produce extra products. This is not assumed in the benefits described above but is also important to consider as increase in production capacity is the main goal of this thesis. This section deals with this subject.

Table 22 shows the full calculation of the potential increase in production capacity per worker. For this, production data of 2020 is used as base for the calculations for three years. With the help of the number of production days, hours per day and the average number of workers per order (see Appendix F.3), the total hours spent on production can be calculated. With the total number of products produced on the line (Appendix F.3), the average number of products per minute per worker can be calculated (0.39).

Using some numbers used in the cost-benefit analysis (decrease in orders per year with a quality issue and the average number of quality issues per order), the total number of prevented issues can be calculated per year. Combining this with the wasted time on quality issues per order (three minutes, see Table 20 and Appendix F.3), the total minutes per worker per year spend on quality issues can be calculated. However, probably more time is wasted due to finishing and switching to a new order and not being useful (talking, working with a low pace, etc.). As it is difficult to give an expected duration to these activities, these are omitted in the estimated duration of three minutes.

Using the average number of products per minute per worker, the increase in production capacity per worker per year can be calculated. A small calculation shows the 126, 328 and 505 more products per worker can be produced in respectively year 1, 2 and 3 when the solutions are implemented. This will probably be even more because of the relatively low estimation of time spent by workers on a quality issue as explained above.

Table 22: Overview of the full calculations for the increase production capacity per worker.

Item	Year 1	Year 2	Year 3
Production days in year (2020)	[redacted]		
Average nr of workers per order			
Minutes per year (with 8 hours per day and 2 workers)		*Censored*	
Total products produced			
Average products per min per worker		0.39	
Production time lost per order		3	
Gem issues per order		2.2	
Orders per year with quality issue prevented	[redacted]		
Total issues		*Censored*	
Total mins spend			
Potential increase in capacity per worker	126	328	505

6.6 Conclusion

This chapter identified solutions to encounter fewer quality issues at the line. To ensure the solutions work in practice, four criteria have been identified the solutions must met: efficiency, practically, user-friendliness and costs. By applying theories from literature, own experiences and organizing a brainstorm session, twelve solutions have been identified. Analyzing these solutions, six solutions have been selected to work out more detailed in an implementation plan: (1) capture and standardize quality assessment procedure of the goods receipt, (2) capture requirements of components/ products, (3) tools for checking quality, (4) move more responsibility to suppliers, (5) more frequent contact with suppliers and (6) reconsider and change suppliers. The implementation plan covers the technical and social side of the solutions as well as the evaluation measures, cost-benefits and potential increase in production capacity. The cost-benefit analysis and analysis of potential increase in production capacity respectively showed that about €19,000 can be saved and a potential increase of 959 (semi-finished) products per worker can be expected in the next three years when implementing the solutions.

7. Conclusions, recommendations and discussion

This chapter concludes the research in which the batch handling of the container-series line has been improved, investigating both batch sizes and quality issues. Section 7.1 provides a conclusion to what extent the chosen core problem has been solved. Next, Section 7.2 outlines the recommendations, subject-related as other more general recommendations. Section 7.3 provides the limitations of the research. Lastly, Section 7.4 identifies possible areas of future work.

7.1 Conclusions

Chapter 3 explained the tool that has been developed to give insight in, gather cycle times and evaluate the effect of using more optimal batch sizes. Based on the results shown by the tool, it has been concluded that the data is generally complete, there were some orders with very small or large cycle times, some outliers were not removed and the cycle times of the laser order were not reliable. Moreover, I concluded that the overall quality and completeness of the data is good enough to use the tool and the data both internally and in the rest of this research.

Chapter 4 described the batch size determination process. Based on the factors identified from multiple sources, batch sizes have been determined. These batch sizes are both positive for the station (reducing cycle times) and the other parts of the company and result in a 12% decrease in (average) cycle times compared with the product-specific average cycle times of the products in the groups. From the sensitivity analysis performed on the batch size determination, it can be concluded that small changes in certain factors do not affect the batch sizes, cycle times and weighted differences of the cycle times of each group heavily. Therefore, batch sizes close to the proposed batch sizes could be used and will have limited effect on the reduction in cycle times. For all other products not analyzed, it would be good to apply a similar procedure as performed in this chapter because a decrease in the cycle times is expected for these as well.

The next chapter, Chapter 5, described the tool that has been made to give insight in the current quality issues. Based on the results shown by the tool, I concluded that the performance (both overall and per supplier) is relatively good but still too many components do have a quality issue. [redacted] In addition, I argued that a trend can be seen in the frequent reasons for rejection, both over all components and per component. Lastly, I argued that the rejection rate (according to the data) for colored components is about the same as components without color.

From the last chapter, I concluded that four criteria are important for a solution to lower the number of quality issues seen on the line, namely efficient, practical, user-friendliness and costs. Based on these criteria, I identified twelve possible solutions. After analyzing these solutions, six have been worked out in an implementation plan. I concluded that the number of orders with a quality issue could be decreased to 17% when using the solutions in the implementation plan. With this decrease, a saving of about €19,000 could be realized in the next three years. Moreover, an extra capacity of 959 products per worker in the next three years is created due to the decrease in issues.

Based on the conclusions of each chapter, I conclude that the core problem is solved. With the help of the tool to give insight in the quality issues and the solutions described in the implementation plan, it is expected that the percentage of order with quality issues at the line decreases from 22% to 17% (goal was 17%). Moreover, the determined batch sizes help to reduce the cycle times with 12% compared with the current average cycle times of the groups, which is almost equal to the goal of 14%.

7.2 Recommendations

This section describes the recommendations that can be deducted from the results of this thesis and of other aspects that were pointed out during this research.

1. To keep insight in both cycle times and quality issues, I recommend **using the two tools** (or similar ones) **frequently**, for example once per month. This way, deviations can be identified earlier and the right-follow up actions can be taken quickly.

2. For the products of which the batch sizes are determined, I recommend using the **proposed new batch sizes** (see Section 4.4.8). These batch sizes reduce cycle times by 12% compared with the current average cycle times of the groups. Moreover, I advise to apply a similar procedure to the products not analyzed, as a decrease in the cycle times is expected as well.
3. To encounter fewer quality issues at the line, a total of twelve solutions were identified. Of these twelve solutions, six are worked out more detailed in an implementation plan. I advise to **implement** these **six solutions** using the implementation plan. Besides, I recommend investigating the feasibility of the other six solutions as well.
4. *Censored* [redacted]
5. At the end of Chapter 5, I identified **several points to ease future analysis** of quality issues: always mention a reason, use reasons from a standardized list, add line for which the component is and add discovery place. Moreover, I recommend investigating frequent reasons for rejection so the right follow-up actions can be taken. It could be, for example, that handling/touching an item with gloves could prevent some quality issues.
6. During my research, the research was heavily dependent on the **cycle times** as recorded by the **current tablet system**. As identified in Chapter 3, the stored cycle times are not always of good quality as these are dependent on the discipline with which the leader of the line starts/pauses/ finishes an order on the tablet. To improve the quality of the data, I advise to change the current system to a system that (1) automatically pauses an order in the break or at the end of the day, (2) clocks workers in separately for each order and (3) has an option to report a malfunction (from a standardized list).
7. One of the problems encountered in the problem cluster and reported by many people within ESS is the **large assortment** assembled on the container-series line. As a consequence of the large assortment, there is a low demand for some products (see problem cluster) and components need to be placed on stock. Therefore, I recommend ESS to investigate and reconsider the assortment of products assembled on the container-series line.
8. During the past few months, one problem recurred in almost every interview performed: **communication**. The communication between departments and between management and the departments is often seen as non-optimal. This is reinforced due to the fact that some departments are located in Oldenzaal, the Netherlands, and others in Bad Bentheim, Germany, (although language difference is not seen as a problem). I recommend spending effort and time on improving the communication, for example through fixed meetings or trainings.
9. During the problem identification, many problems negatively influencing the production capacity were identified (see Section 1.3 and Appendix A). Three problems have been selected as core problem and solved in this research. The other problems, however, may also have a large effect on the production capacity. Therefore, I advise **investigating other problems** of the **problem cluster** as well.

7.3 Limitations

Just as every research has some limitations, this research also has limitations. I have identified the following limitations:

- **Tools as good as data quality**. To give insight in both cycle times and quality issues, two separate tools have been constructed. The quality of the results, however, are completely determined by the quality of the input data and, as a consequence, false results can be shown.
- **Not enough data**. To draw a strong conclusion about a relation between two variables, enough data is needed as otherwise there is a high risk of drawing a false conclusion (see Section 4.2.3). As there is limited data available, it can be that a false conclusion is drawn about the existence of a (statistical) relation. Moreover, the data could consist of too few different batch sizes.
- **Poor quality of data**. The quality of the cycle time data is dependent on the discipline with which the worker responsible for the tablet records the time of the order in the correct way. As this discipline is not always high (see Chapter 3), the quality of the data is not always high. Because the used method is heavily dependent on the data, the conclusion can be incorrect due to the poor quality of data.

- **Historical data may not be the best base for determining batch sizes**. While there seems to be a relation between batch size and cycle time, this may be coincidence. The found relation may completely be a result of randomness and, therefore, not a good base for selecting a batch size. Besides, the correlation between the variables is sometimes very low (indicated by the correlation coefficients) and may, therefore, not be a good base. Other bases, for example formulas, (linear) programming or queuing, may possibly be more suitable bases.
- **Data interpretation**. During the investigation of the relations in the batch size determination process, trends have been analyzed and visualized in trendlines. As this analysis and visualization is heavily influenced by personal interpretation, it is possible that one detects other trends and draws other trendlines than other persons. Therefore, other conclusions about batch sizes can be drawn.
- **General relation factors may not hold**. At the goods receipt and the picking, a general relation between the number of components and time it takes is measured and investigated instead of products from the product mix. It could be the case, however, that the identified general relation does not hold for certain specific products because of certain characteristics. As the conclusions are partly based on this relation, the determination of batch sizes can be affected.
- **Not all aspects considered**. It could be the case that not all aspects of a factor are identified and researched, for example the discount when buying larger quantities at suppliers (only treated qualitatively). This can lead to other batch sizes than when these are included.
- **Product groups too aggregated**. In order to have more data available, products with the same features are aggregated (i.e., same product, different color, dimensions). Products can, however, still differ a lot per factor. Therefore, the determined batch sizes from the historical data of the cycle times and batch sizes may not hold for certain products.
- **Assumptions implementation plan may not be correct**. In the implementation plan, some assumptions had to be made. To construct a time plan, assumptions regarding responsibility and durations had to be made. Moreover, some assumptions in the cost-benefit analysis and in the analysis of the effect in production capacity had to be made regarding the components, durations, effect and costs. It could be that some of these assumptions are not completely true, which results in other values than expected.

7.4 Future work

Due to the limited amount of ten weeks, choices in the scope had to be made. If the execution time had been longer, more subjects could have been included. This section identifies the possible future work identified during the executing of the thesis.

- **Determine batch sizes of more products**. Due to limited amount of time, only the batch sizes of some products have been determined. In the future, the same process could be applied to more products on the line to also determine their batch sizes.
- **Layout of line**. This thesis focused on increasing the capacity of the line by changing batch sizes and the number of quality issues. Another aspect in the capacity, however, is the layout of the line which is currently not optimal. Research can be done on the most optimal layout.
- **Layout of the production facility**. As the layout of the line, the layout of the production facility is not optimal. Due to this suboptimal layout, the workers on the line have to walk much during the assembly of an order to gather materials. This results in unnecessary walking time and, thus, waste. By changing the layout, this waste could be reduced to a minimum.
- **The stock of components**. Although the utilization rate of the components warehouse is high, the stock of some components (and especially the semi-finished products used across multiple products) is low. Therefore, I recommend investigating the stock levels of these components, as these are often the limited factor in production.
- **Weighting bulk components.** Currently, the quantities are assumed to be correct if reasonable. I recommend investigating the feasibility of a weighting principle to check the quantity of bulk components in terms of practical reasons, costs and benefits.
- **Route pickers**. The scanners of the pickers show the route to pick the components of a pick order. This route, however, is not optimal as this does not consider quantities or other characteristics (for example possibility of scratches or extra-long lengths). Therefore, research could be performed to the optimal route considering all these factors.

8. Reference list

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A. Full explanation problem cluster

This appendix provides a detailed explanation of the problem cluster and the problems contained within the cluster. Each category of the problem cluster is discussed in a sperate section.

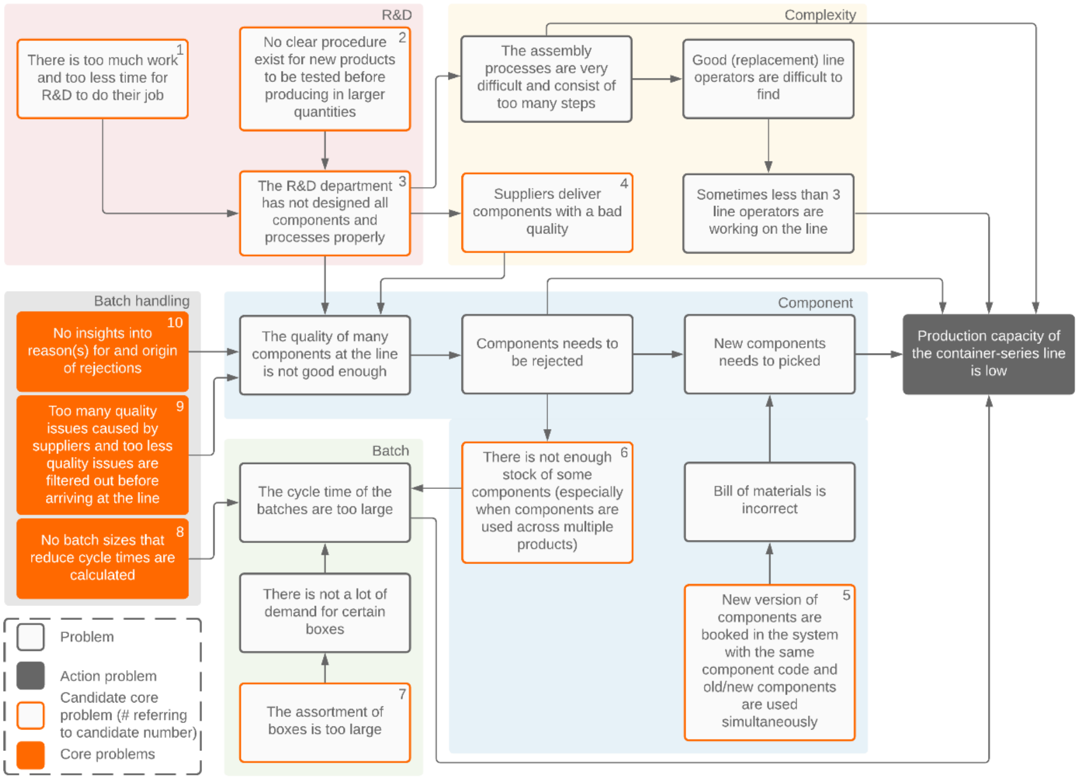


Figure A-1: Problem cluster containing problems that play with regard to the action problem "low production capacity of the container-series line".

Figure A-1 depicts the problems that directly and indirectly cause a low production capacity of the container-series line. Five categories of problems can be identified, these are: R&D, complexity, batch, component and batch handling. Each of the categories and the problems within will be shortly explained below.

A.1 R&D

The first category, the R&D, is the red group in Figure A-1. The problems within this category all have something to do with the R&D department. The main problem is that the R&D department has not designed all the components and process properly. This problem causes three other problems: bad quality of the components (component category), suppliers that deliver components with bad quality (complexity category) and processes that are very difficult and consist of too many steps (complexity category). These will be explained in the next subsections. The poor design by the R&D department has also two problems by which it is caused.

First, there is a high workload and limited amount of time available for the R&D department. This makes that they do not have enough time to make a proper design of all products and processes. Secondly, there is currently no clear procedure available for new products to be tested. This means that for new products, there is either a very vague and short test order made or no test order at all. With these test orders, design flaws and other problems are identified and can be solved before the normal order is produced. This way, the assembly will not have to stop and lose unnecessary time. And even if there is a test order now, most of the time the "real" (normal) production order is scheduled a couple of hours later. This means that there is no time to solve the problems identified during these test orders and it might as well not happen.

A.2 Complexity

The second category, complexity, consists of a total of four problems. Complexity is the yellow group in Figure A-1 and contains all the problems relating the complexity of the line. The first problem within this category is that the assembly process is very difficult and consists of too many steps. This problem is a result of the not fully continued development of the products and processes by the R&D department, as described in the previous paragraph. The not fully continued development problem also (partly) causes another problem in the complexity category: bad quality of components by the suppliers. Because difficult components are used in the process, components are difficult to produce and often contain a quality issue. These issues affect the overall quality of the components used.

The problem of a very difficult assembly process, in turn, causes two other problems. First, the number of products that can be made (and thus the capacity) on the line is low as it costs a lot of time to assemble one product due to the complex process. Second, it is hard to find good operators for this line due to the high complexity of the process. At the moment, three operators are working on this line and they are all three highly skilled. When one of these operators either leaves the company or is absent for a limited amount of time (e.g., free day or ill), it is very hard to find a replacement worker. When a worker is absent, currently no one will replace that worker and thus less than three operators are working on the line. This, in turn, also lowers the capacity of the container-series line.

A.3 Batch

The third category in Figure A-1, the batch category, is depicted green and contains all the problems relating to batches. A first problem within this category is that no optimal batch sizes (too small batch sizes) are used on the container-series line. Because of these batch sizes, the average time to assemble a product (cycle time) is relatively high. This problem, in turn, is caused by three other problems.

First, the demand for certain products is not sufficiently high. It is for ESS not profitable to make these products in larger batch sizes because this increases the risk of not being able to sell the products anymore. Besides, the inventory of these products will also increase if the products are made in larger batch sizes and with that, the total holding cost of the company. One of the reasons why there is not a lot of demand for some products is that the assortment is very large, so the demand for the products is spread over a lot of different products.

Second, the inventory of some components is too low, especially for components which are used across multiple products. This problem belongs to another category (component) and is explained fully in Section A.4.

The third and final problem is that the optimal batch sizes are not calculated yet and is one from another category: batch handling. This problem is explained below in the last subsection.

A.4 Component

The fourth category is a complex category and consists of many problems. This category is blue in Figure A-1 and contains the problems relating the components. Starting at the left side of Figure A-1, the quality of the components is not always good. This is the consequence of three problems. First, the R&D department that has not designed everything properly. Consequently, the R&D department has developed components which are difficult (or impossible) to make for the suppliers (or have bad quality measures like tolerances), resulting in more quality issues with the components (like scratches, non-conform color or non-conform dimensions). Besides, suppliers also produce components (without complexity) with a bad quality, which also affects (lowers) the quality of the components.

Moreover, this poor design results in an assembly process that is very difficult. This means that there is a higher chance of damaging the component(s) (like making scratches) during the assembly process and, with that, a higher change of quality issues. The second and third problem, no insight in the reason(s) for rejection and no clear procedure at the goods receipt, also causes a bad quality of some components and are problems from the category batch handling. Because of that, these problems are discussed in more detail below.

The poor quality of some components causes that some components need to be rejected due to these quality issues. Consequently, the production capacity, number of (good) products that are assembled on this line, is low. Another consequence of the poor quality is that new components need to be picked again if components are rejected due to a quality issue. The result of this is that more time will be spent on picking and waiting for the new components then necessary. This also directly affects the production capacity of the container-series line.

The repicking of components can also have another reason, namely an incorrect bill of materials. Sometimes, this happens because a newer version of a component is booked in the system with the same code as the original one and these two versions are used simultaneously. So, it can happen that an “old version” of a door is needed in a frame, while the pickers have picked a “new version”. This way, a new task must be given to the pickers to collect and distribute the right version (in this case the “old version”). The workers on the line need to wait for the new component before they can finish the product and continue with another product. Thus, time is lost which could be used to assemble products and, consequently, the production capacity is lower.

The rejections due to quality issues also cause a lower inventory of components, which also affects the batch sizes (as explained above). Although most of the components are not high value components, it is chosen to keep the inventory of some components at a (relatively) low level. This is because, as explained in the section batch, the demand for certain products (and thus components) is not very high. So, the turnover rate of some components is very low. Consequently, the holding cost of some components will increase drastically if larger inventories are used. Due to the low inventory of some components and the rejections which makes the inventory even lower, the production planner cannot plan orders with higher batch sizes. This is simply because the components are not available. And if the components are available, these need to be distributed among several orders.

A.5 Batch handling

The final category is orange in Figure A-1 and consists of three problems. The first problem is that there is no (clear) insight into the quality issues themselves. It cannot be seen in one clear overview (1) how much quality issues appear, (2) at what supplier(s) and (3) what the reason(s) is/are for this. Because this is not clear, no real actions are taken against certain suppliers to increase their quality.

Second, there are too many quality issues at suppliers and too few quality issues are filtered out. This way, too many quality issues are seen at the line itself. Because the quality issues are discovered so late in the process, it has a major impact on the production capacity as new components have to be picked, the order size needs to be decreased or the order must be postponed.

Thirdly, the optimal batch sizes are not calculated. Currently, the used batch sizes are based on feelings of the production planner and not substantiated with calculations. Because of that, non-optimal batch sizes (smaller) are used that have a (relative) large cycle times. This means that more time is spent then is necessary and thus lowers the production capacity of the line.

B. Flow diagrams of the processes

Appendix B contains the process flows constructed to describe the current situation. A description of these process flows can be read in Chapter 2. Each section contains a process flow of a different part of the production facility.

B.1 Production facility

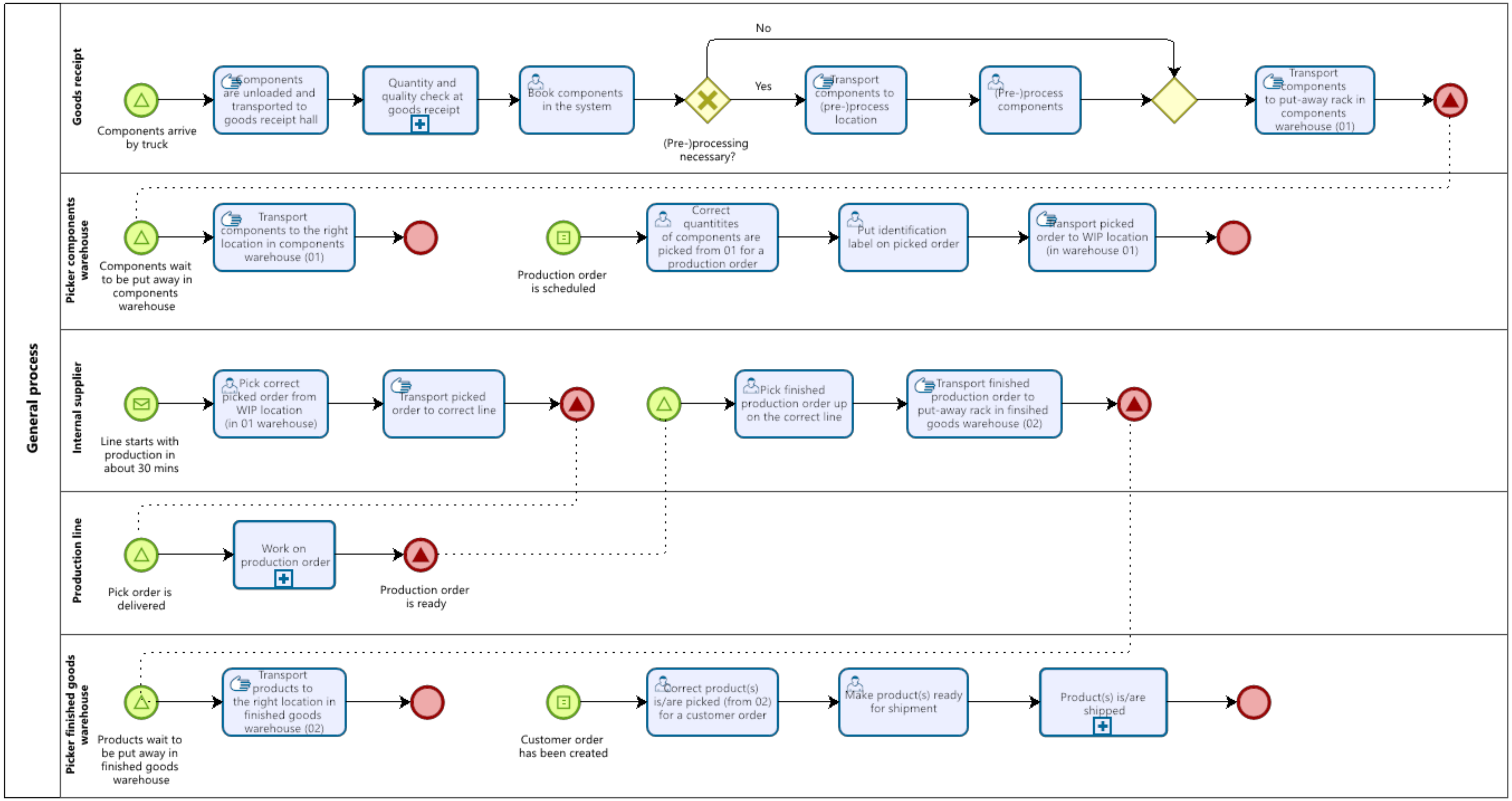


Figure B-1: Total overview of the assembly process of ESS.

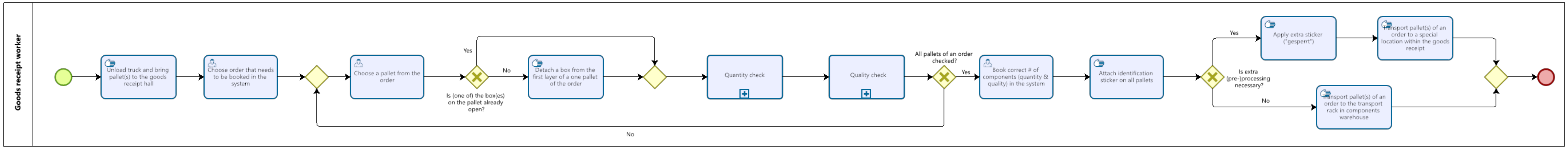


Figure B-2: General overview of the goods receipt process.

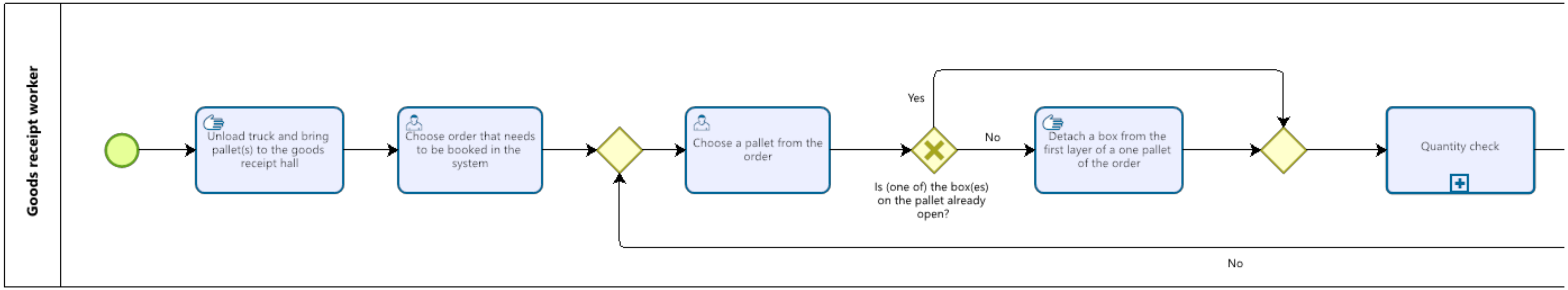


Figure B-3: General overview of the goods receipt process more detailed (1/2).

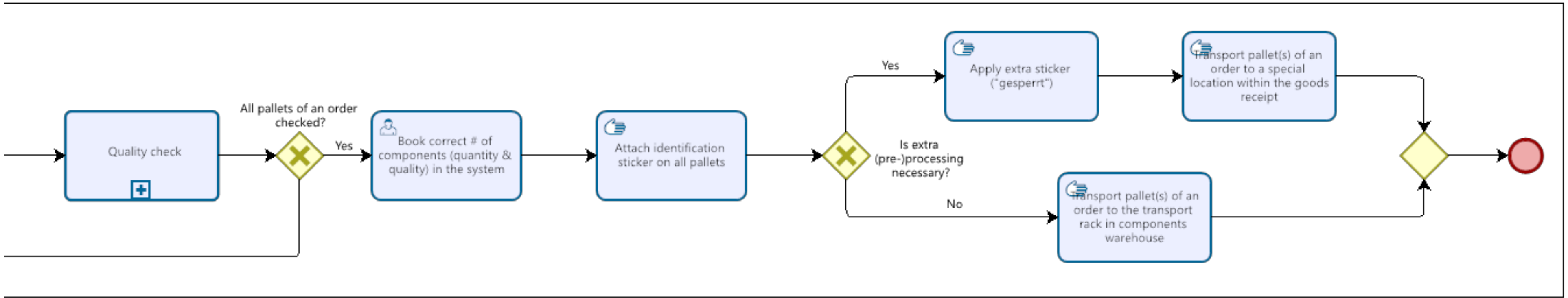


Figure B-4: General overview of the goods receipt process more detailed (2/2).

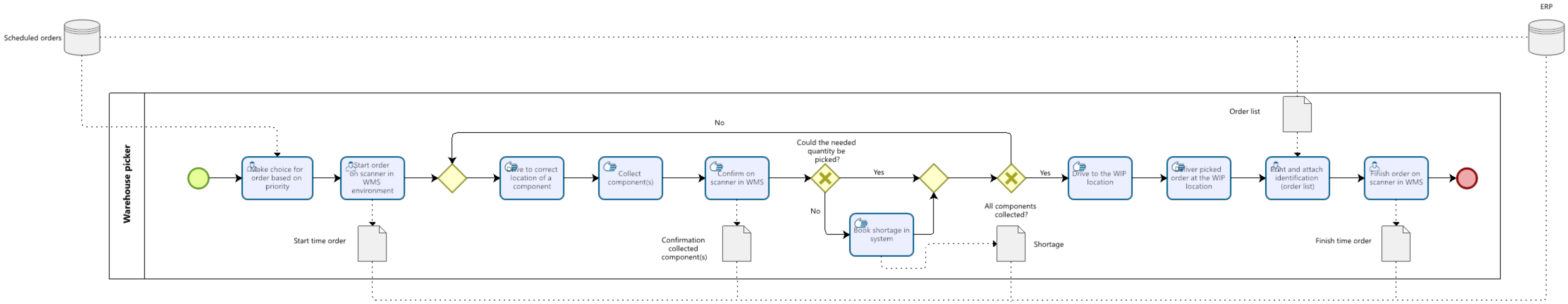


Figure B-5: Pick process of warehouse pickers related to the container-series line.

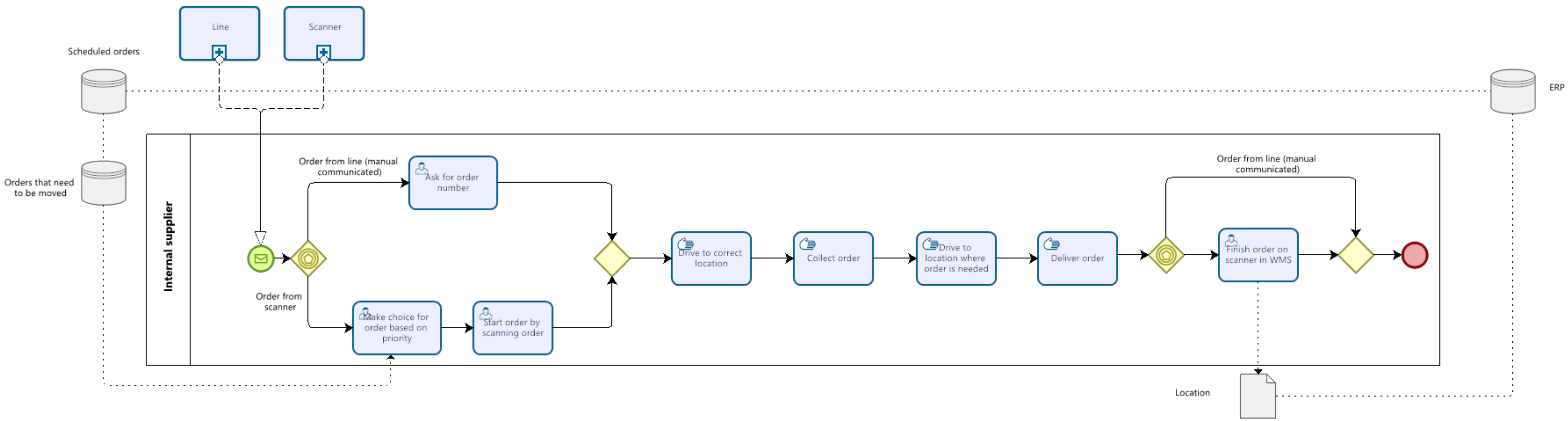


Figure B-6: Pick process of internal supplier related to the container-series line.

B.2 Container-series line

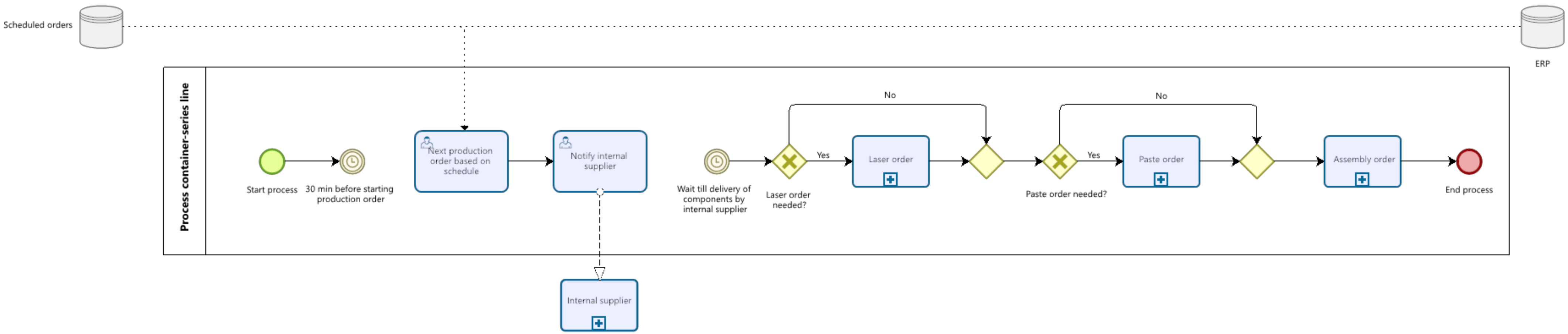


Figure B-7: General process of the container-series line.

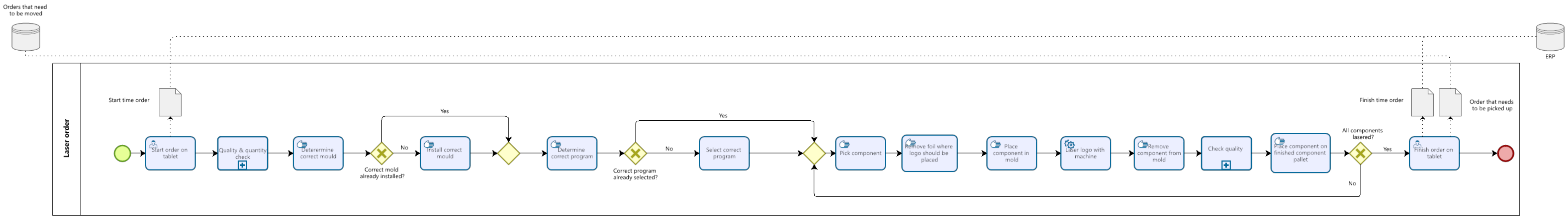


Figure B-8: Overview of the laser order on the container-series line.

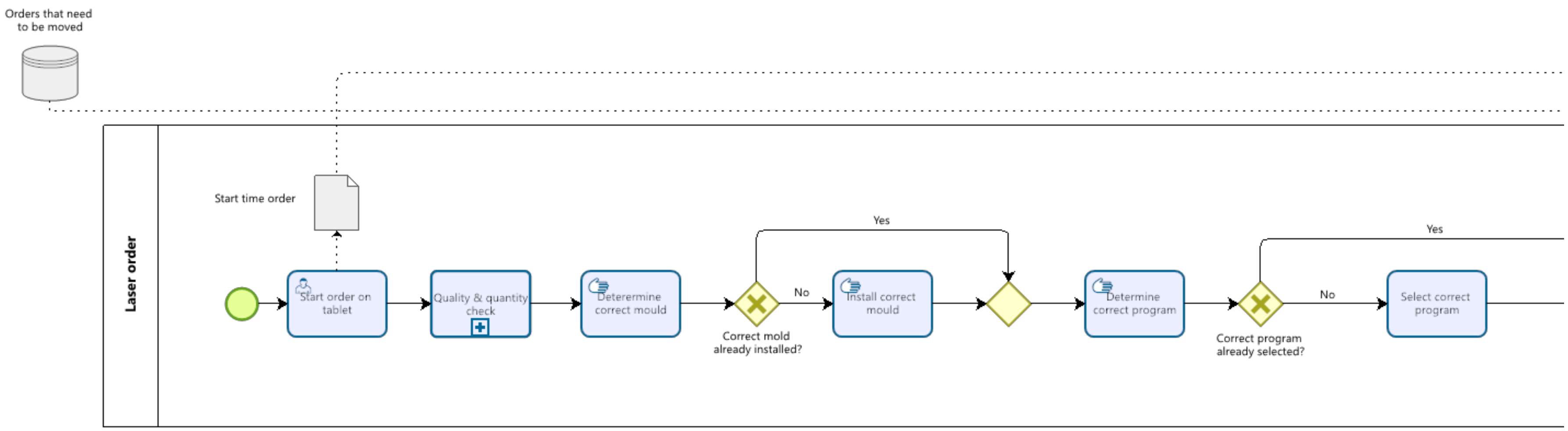


Figure B-9: The laser order in more detail (1/2).

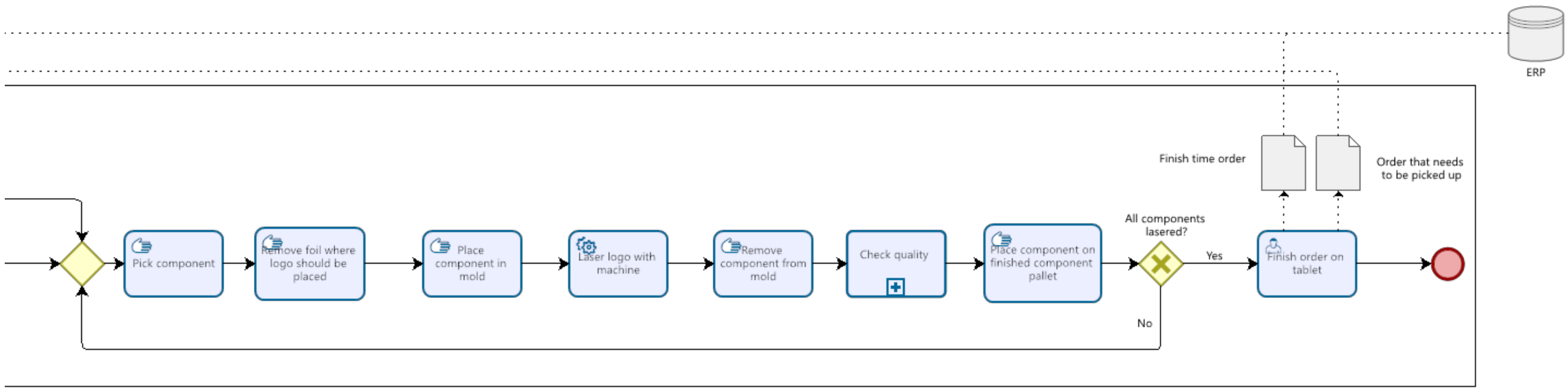


Figure B-10: The laser order in more detail (2/2).

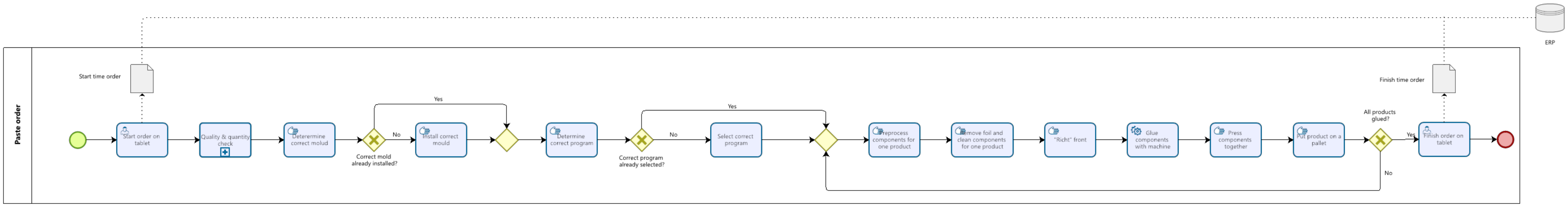


Figure B-11: Overview of the paste order on the container-series line.

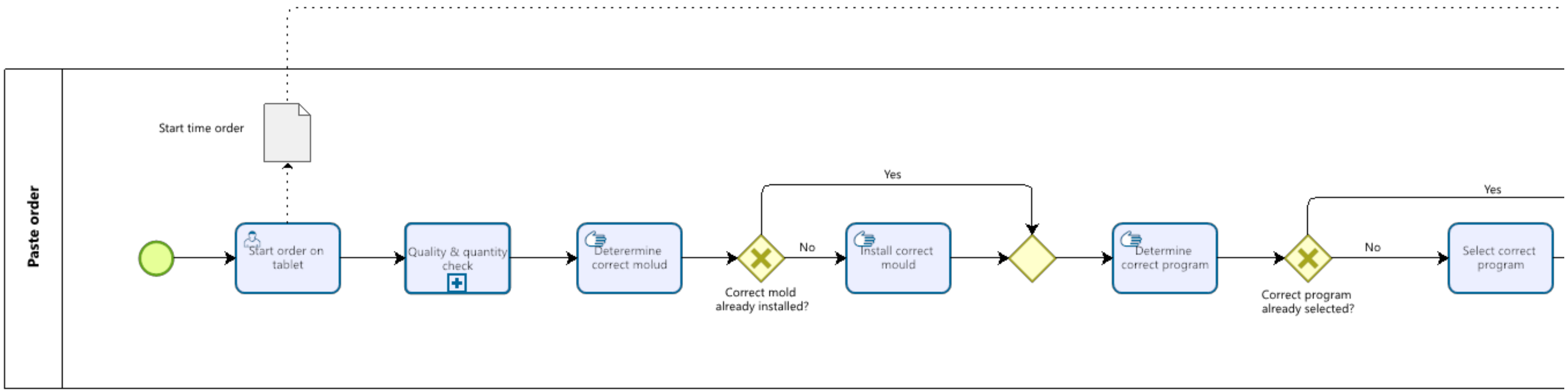


Figure B-12: The paste order in more detail (1/2).

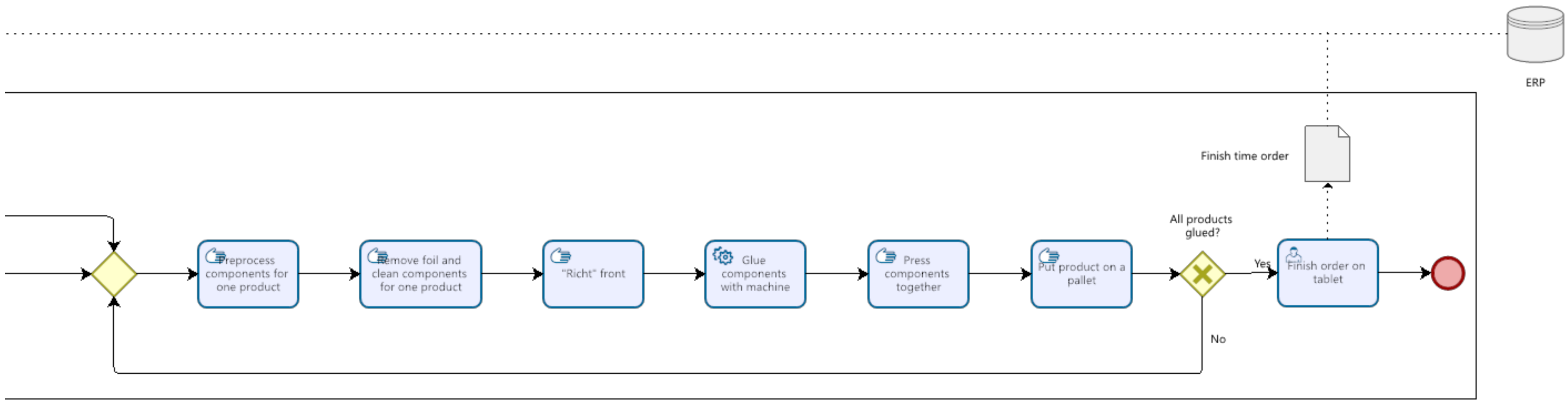


Figure B-13: The paste order in more detail (2/2).

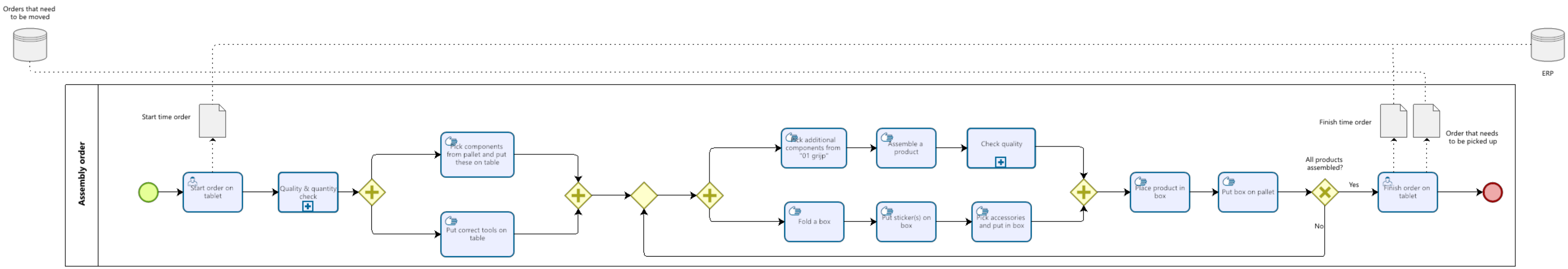


Figure B-14: Overview of the assembly order on the container-series line.

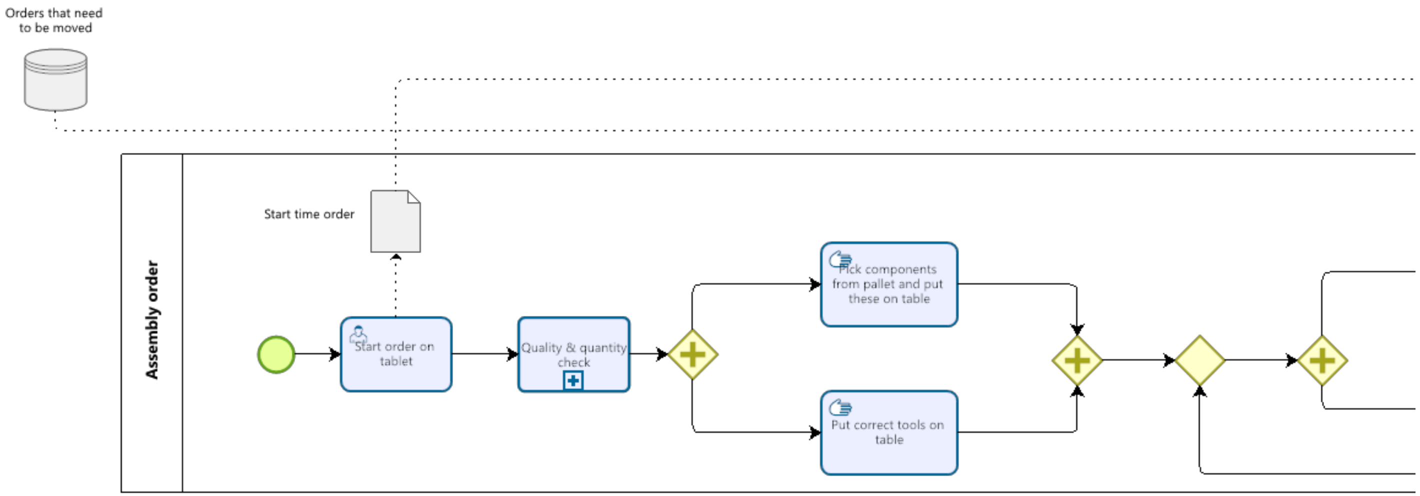


Figure B-15: The assembly order in more detail (1/2).

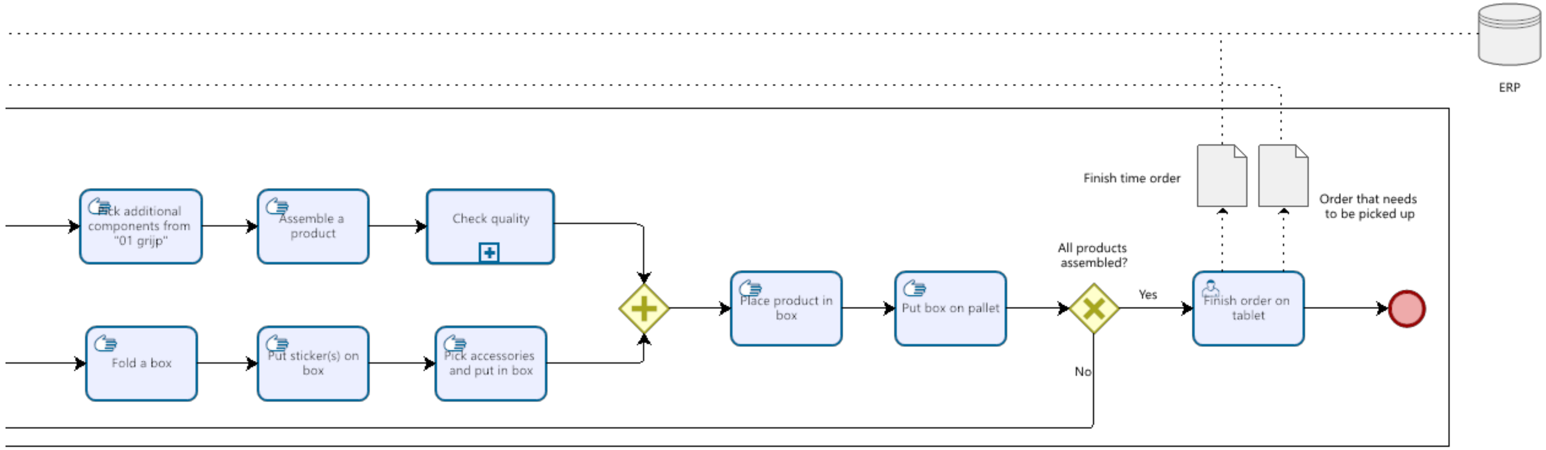


Figure B-16: The assembly order in more detail (2/2).

B.3 Goods receipt

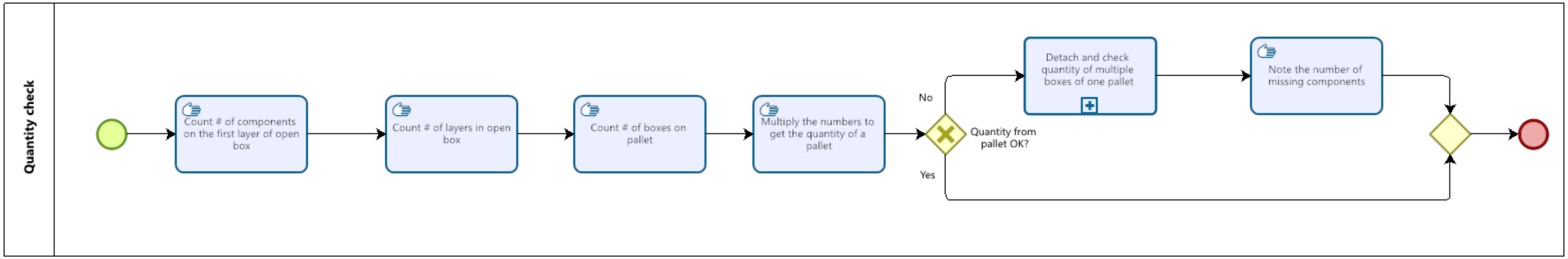


Figure B-17: Quantity assessment procedure at the goods receipt.

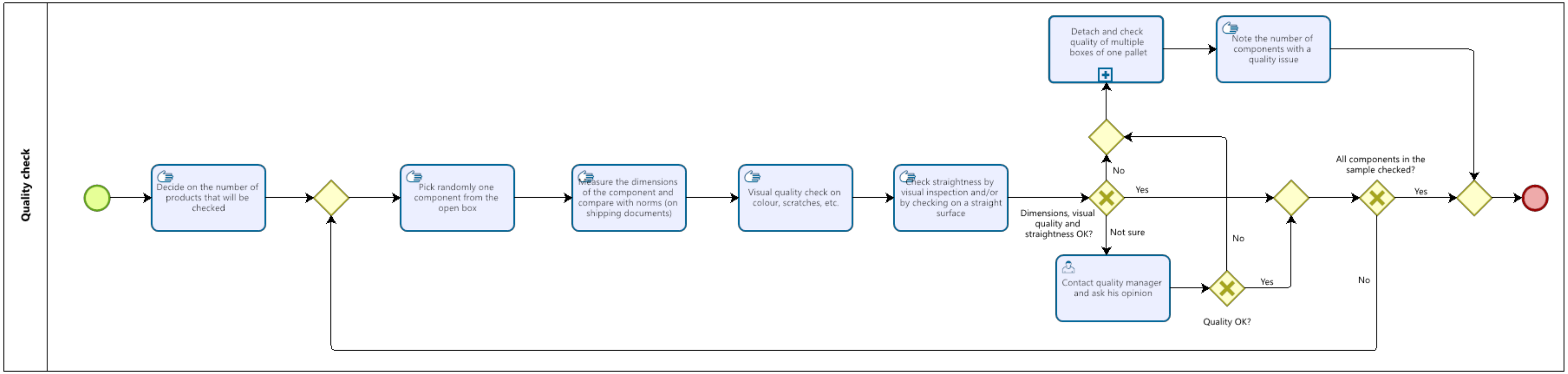


Figure B-18: Quality assessment procedure at the goods receipt.

C. Description cycle time tool

Appendix C contains an explanation of the cycle time tool that has been constructed. The cycle time tool consist of nine sheets, each having its own function. The sheets within the tool are explained separately in the subsections below. A screenshot of each screen, including other interesting screens, can be seen in Section C.10. This appendix ends with Section C.11, in which some results of the cycle time tool are depicted.

C.1 Sheet 1: "DATA"

Figure C-1 depicts the sheet "DATA" of the cycle time tool. This sheet contains the raw production data of all assembly lines (1-10) extracted from the ERP system. Each row of the sheet is a status change of an order on one of the lines. Among others, it contains the following information:

- **ID**: created by the ERP system for each status change;
- **LogDate**: date when change is recorded in the ERP system;
- **DocEntry**: distinct number created by the ERP system for each order;
- **Status**: one of the following three statuses is assigned to an order: Start, Onhold or Finished;
- **Username**: line number on which the order is assembled to distinguish between lines;
- **DocNum**: the order number of an order used internal (different from DocEntry);
- **ItemCode**: name of the article assembled in the order.
- **Planned & Completed quantity**: the number of products that are respectively planned and actual assembled in an order.
- **ProdMensAantal**: the number of workers that have worked on the order (can be different for different orders assembled consecutively on the same line).
- **Δ Time**: The time that is passed in between two rows (status changes) of the same order.
- **Δ ProdTime**: The actual production time that is passed in between two rows (status changes) of the same order.

The format of this sheet is the same as when an extraction from the ERP system is performed. Therefore, the extraction can be simply exported in Excel and no formatting or sorting of the data is necessary as these actions are performed by the tool itself. The only function of the sheet is to provide the data for the rest of the tool to work correctly.

C.2 Sheet 2: "CT"

A screenshot of the worksheet "CT" can be seen in Figure C-2 and the control button in Figure C-3. By pressing the button "Sort DATA", the data in the first worksheet is first sorted on "DocEntry" (so the data of one order is grouped together) and second on "ID" (so the data of the orders is chronological). When the data in this first worksheet is not sorted correctly, the tool does not work properly.

Next to the "Sort DATA" button, there is a dropdown menu in which one of the ten lines can be selected. By pressing the button "Export", all the data of the selected line is exported from the sheet "DATA" to the current sheet. It is chosen to export the data of the selected line in a separate sheet to speed up the calculations performed later.

As all the data is copied 1:1 from the "DATA" sheet and this sheet contains the raw production data, the quality of the data is not very high. For example, some orders are started multiple times (within a couple of seconds), paused multiple times or not finished at all. Therefore, to perform analysis on the data, the data must be cleaned first. A macro in VBA has been created that automatically checks for these kinds of issues and performs the right follow-up action. Each case that is in theory not possible is analyzed separately to determine, build and verify the right follow-up action.

The case when an order is started multiple times, for example, has been solved by deleting the first row containing this first start status. For some reason, the order is started multiple times but the recording of the rest of the order is perfectly fine. By pressing the button “Check”, the above-described check and follow-up actions are performed automatically by the tool.

C.3 Sheet 3: “CT2”

Figure C-4 depicts the third sheet of the tool, named “CT2”. The aim of this sheet is to aggregate all rows of one order in the previous sheet into one row. Only the information that is needed from the previous sheet is copied and used in the calculations. Besides, the category of the product is copied to the sheet (only applicable for products assembled on line 5, see Section C.6).

Besides simply copying the data of an order from the previous sheet, three measures are calculated: (1) the cycle time per order, (2) the cycle time per product (on average) and (3) the cycle time per product multiplied with the number of workers that have assembled the order. This last one is a measure of the total amount of time that is spent on assembling the product and is used later to make a comparison between orders (see next section).

C.4 Sheet 4: “CT3”

The fourth sheet “CT3” contains an overview of the cycle times of all orders of a certain (semi-finished) product and can be seen in Figure C-5. On the dashboard on the right side of the screen, a line (or type of order in case of line 5, laser, paste, assembly or all) can be selected via a dropdown menu. Based on the line/type selected, a (semi-finished) product can be selected in the dropdown menu from all (semi-finished) products of the line/type. When a (semi-finished) product is selected from the dropdown menu, the tool automatically finds all the order numbers (DocNums) of the (semi-finished) product selected. These order numbers are from the sheet “ListOfProducts2” (see Section C.8) and copies these to the second column in sheet “CT3”.

When all order numbers (DocNums) are found and copied to the sheet, the tool copies the relevant rows from the previous sheet (“CT2”) to the current sheet. When the information of a row cannot be found in the previous sheet, the row is marked red. There are two reasons why there is no information available of an order: (1) the order was scheduled in the production schedule (and thus included in “ListOfProducts2”, see Section C.8) but not actual produced and (2) the order is removed by the cleaning of the data in the sheet “CT”.

When all rows are filled with information, the graphs and numbers displayed on the dashboard are automatically updated. The graph types within the dashboard are based on the literature findings about the best way to present data (Section 3.2.1). The dashboard can be seen more detailed in Figure C-6 and contains the following information (enumeration corresponds with numbers in Figure C-6):

1. The **assembly line or type** of order (in case of line 5) selected;
2. The **product** from the line or type selected;
3. The **average cycle time per order**;
4. The **average cycle time per product**;
5. The **average cycle time per product multiplied with the number of workers**;
6. The number of orders (**number of datapoints**);
7. The number of **distinct/unique batch sizes**;
8. Scatterplot of the **cycle time per order vs orders**;
9. Scatterplot of **cycle time per product vs orders**;
10. Scatterplot of **cycle time per product multiplied with the number of workers vs orders**;
11. Histogram of the frequency of the **cycle time per product multiplied with the number of workers**;
12. Scatterplot of the **cycle time per product multiplied with the number of workers vs batch size.**

The tool also calculates the classical numerical summary for the three cycle time measures, consisting of sample size, sample variance, sample standard deviation, sample skewness coefficient and sample kurtosis (Meijer, 2018). The classical numerical summaries are displayed in the (most upper) table above the dashboard (see Figure C-5). Moreover, the table with information about outliers is filled by the tool. This table calculates the first quartile (Q1), third quartile (Q3), interquartile range (IQR= Q3-Q1), the lower bound (LB) and upper bound (UP) for each of the three cycle time measures. See Section 3.2 for a more detailed explanation of the detection and handling of outliers.

By pressing the button “Outliers”, a pop-up screen appears (see Figure C-7) in which a method for the detection of outliers (‘custom borders’, ‘1.5 x IQR’, ‘3 x IQR’ or ‘3 x s’) and for handling outliers (‘none’, ‘trimming’ or ‘winsorization’) can be selected from two drop-down menus. By pressing the button “Cancel” or clicking the cross at the upper right of the pop-up screen, the pop-up screen is closed and no further actions are executed. By pressing the “OK” button, the tool calculates the correct borders for the third measure: the ‘cycle time per product multiplied with the number of workers. It is chosen to use this measure as it eliminates the differences in the number of products and workers per order between the different orders. Thus, this measure can be used to compare different orders with each other. In case the option ‘custom borders’ is chosen, another pop-up screen appears (see Figure C-8) in which the lower and upper bound can be set by the user.

After the borders are calculated, the tool applies the chosen method of handling outliers to the orders falling outside the borders (i.e., orders with a cycle time, per product multiplied with the number of workers, lower than the lower bound or larger than the upper bound). In case the option “None” is chosen, the row(s) of the outlier(s) are only marked yellow. When trimming is chosen, the row(s) containing outlier(s) is marked yellow and the all the information of the row is deleted, except for the first four columns (DocEntry, DocNum, Itemcode and planned quantity). Lastly, when the option ‘winsorization’ is selected, the row is marked yellow and the ‘cycle time per product multiplied with the number of workers’ is replaced by either the lower bound (in case the value was lower than the lower bound) or by the upper bound (in case the value was larger than the upper bound). The other two cycle time measures are charged back from the value by which the third cycle time measure is replaced. When the outliers are adjusted/deleted, the tables (above the dashboard), graphs and numerical values in the dashboard are updated.

When a new product is selected in the dashboard, the sheet is cleared and the complete process is repeated: all the order numbers are copied, the corresponding information is copied and all values and graphs updated.

C.5 Sheet 5: “CT4”

The fifth sheet is called “CT4” can be seen in Figure C-9. The aim of this sheet is to create an overview of the same numerical values as in the dashboard of the sheet “CT3”. The difference, however, is that instead for one (semi-finished) product, these numerical values are calculated for all (semi-finished) products of a line or of a type. In the dashboard on the right side of the sheet, a line/type can be selected. Besides, the right method to detect and handle outliers (same options as described previously) can be selected via a drop-down menu.

By pressing the button “Calculate”, an analogous process as described for the previous sheet is initiated. The difference with the last sheet is that (1) all the data is instead of copied to the sheet stored in an array, (2) outliers are removed directly (or not in case ‘None’ is chosen in the drop-down menu) and (3) only the sum or average value for the (semi-finished) product is depicted. As this process is executed for all (semi-finished) products of a line or type, this process takes a couple of minutes.

When the numerical values of all orders are calculated, the user can choose to detect and handle outliers over all (semi-finished) products instead of within a (semi-finished) product. The options to detect and handle outliers are the same as for described in the previous section. The detection and handling method can be chosen by using two drop-down menus in the dashboard. The actual detection and handling can be initiated by pressing the button “Outliers over all products”.

Figure C-10 depicts the dashboard that is made for this sheet. The graph types on the screen are based on the literature about the best way to present data (see Section 3.2.1). The dashboard contains the following information (enumeration corresponds with numbers in Figure C-10):

1. **Numerical values** that are calculated in the process of **determining and handling outliers** over all orders and includes: Q1, Q3, IQR, LB, UB and the standard deviation (s);
2. The selected **line/type**;
3. The selected **outliers detection and handling method within** each (semi-finished) product;
4. The selected **outliers detection and handling method over all** (semi-finished) product;
5. The value of the **borders** for each of the **outliers detection method**;
6. The **number of (semi-finished) products** of the selected line/type;
7. The **global average quantity assembled** (average over the average quantities assembled per (semi-finished) product);
8. The **global average number of workers** (average over the average number of workers per (semi-finished) product);
9. The **global average cycle time per product** (average over the average cycle times per product per (semi-finished) product);
10. The **global average cycle time per product multiplied with the number of workers** (average over the average cycle times per product multiplied with the number of workers per (semi-finished) product);
11. The **average number of distinct batch sizes** per (semi-finished) product;
12. The **average number of orders** per (semi-finished) product;
13. A plot of the **(average) quantity** per (semi-finished) product;
14. A histogram of the **frequency** of the **average number of workers**;
15. A histogram of the **frequency** of the **category** (not considering the number of products per (semi-finished) product and only in case of line 5);
16. A histogram of the **frequency** of the **number of distinct batch sizes**;
17. A histogram of the **frequency** of the **number of orders per product**;
18. A plot of the **(average) cycle time per product** for all (semi-finished) product;
19. A plot of the **(average) cycle time per product multiplied with the number of workers** for all (semi-finished) products.

C.6 Sheet 6: “CT5”

The sixth sheet of the cycle time tool is a sheet that is only applicable for the products of line 5 and can be seen in Figure C-11. As some (semi-finished) products do have no or very little orders, the calculated cycle time is not representative for the actual cycle time. To be able to draw a stronger conclusion about the cycle times, the (semi-finished) products are grouped in categories. These categories are from the sheet “ListOfproducts” (see next section). Not all (semi-finished) products have been assigned a category. The products that do not have a category are the first one listed in the overview. Afterwards, the values of the categories are calculated (analogous to the process described in the previous section), The dashboard created for this sheet is analogous to the dashboard of the previous sheet and can be seen in more detail in Figure C-12. Again, the graph types are based on the literature findings on data visualization (see Section 3.2.1). The dashboard contains the following information:

1. The selected **outliers detection and handling method within** each category;
2. The **number of categories** (including products without a category);
3. The **global average quantity assembled** (average over the average quantities assembled per category);
4. The **global average number of workers** (average over the average number of workers per category);
5. The **global average cycle time per order** (average over the average cycle times per order per category);
6. The **global average cycle time per product** (average over the average cycle times per product per category);
7. The **global average cycle time per product multiplied with the number of workers** (average over the average cycle times per product multiplied with the number of workers per category);
8. The **average number of orders** per category;
9. A plot of the **(average) quantity** per category
10. A plot of the **(average) cycle time per order** per category;
11. A plot of the **(average) cycle time per product** per category;
12. A plot of the **(average) cycle time per product multiplied with the number of workers** per category;
13. A histogram of the **frequency** of the **average number of workers**;
14. A histogram of the **frequency** of the **number of orders** per category;

C.7 Sheet 7: "ListOfProducts"

A screenshot of the sheet "ListOfProducts" can be seen in Figure C-13. This sheet contains an overview of all the (semi-finished) products of a line or type. Besides, the categories of the products are listed (only for the products on line 5). This sheet is used by the cycle time tool to (1) have the correct (semi-finished) products in the drop-down menus and (2) calculate the correct information of all (semi-finished) products of a line or type (for sheets "CT4" and "CT5"). No user interaction is necessary on this sheet. The only function it has is to provide input about the (distinct) (semi-finished) products of a line or type.

C.8 Sheet 8: "ListOfProducts2"

The eighth sheet of the cycle time tool is called "ListOfProducts2" and is depicted in Figure C-14. Per line, it provides an overview of all products and the belonging production numbers. The information comes from the production schedule and is transformed in such a way that all order numbers (DocNums) of a product are listed beneath each other. The cycle time tool uses the information in this sheet to find all order numbers of a certain product. These order numbers are used in the code that is used to fill the sheets "CT3" and "CT4". When data of a new period is loaded, the user has to paste the information from the production schedule in this sheet to make sure the tool is able to find all order numbers. No interaction of the user is necessary on this sheet.

C.9 Sheet 9: "Validation"

A screenshot of this sheet can be seen in Figure C-15. This sheet contains information that is used in the drop-down menus throughout the screens. This sheet only has one function: it ensures that the drop-down menus are filled with the correct options. When more options need to be added in the future, other options can be added here. As this sheet is only used to provide the drop-down menus with the correct information, no interaction of the user is necessary on this sheet.

C.10 Screenshots

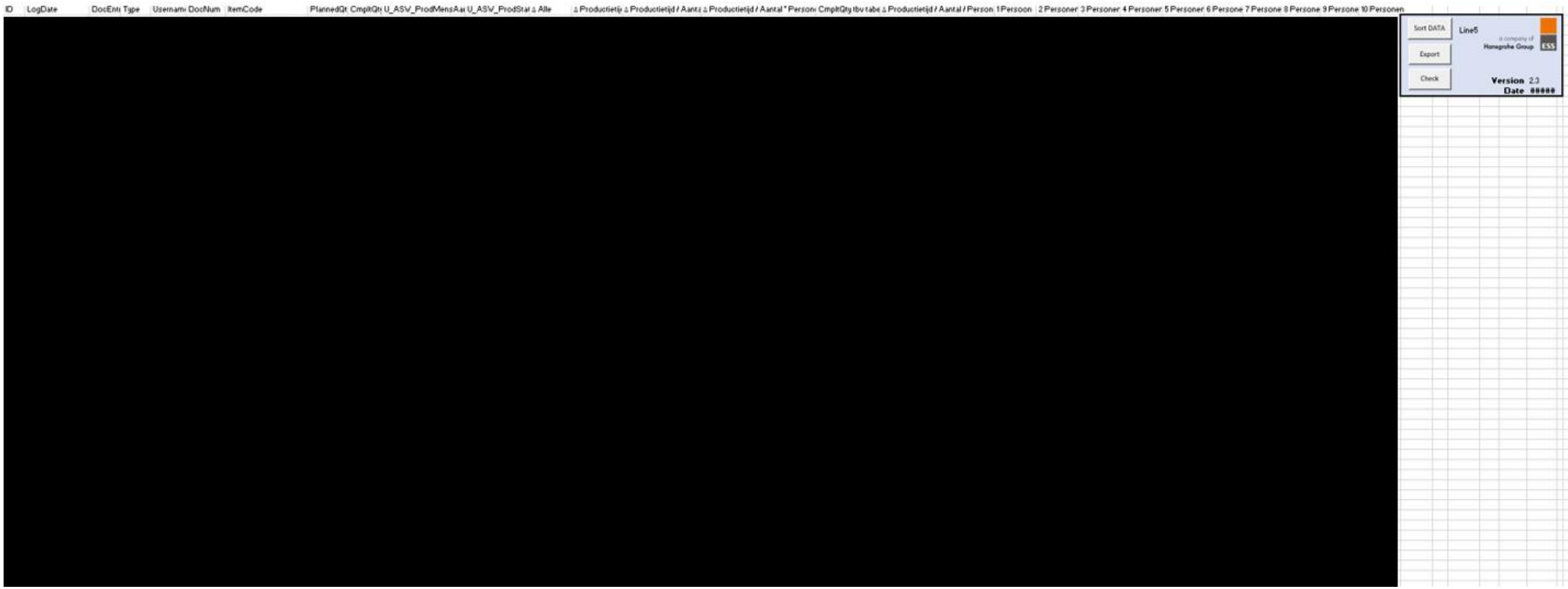
C.10.1 Sheet "DATA"

ID	LogDate	DocEntry	Type	Username	DocNum	ItemCode	PlannedQty	CmpltQty	U_ASV_ProdMensAant	U_ASV_ProdStatus	Δ Alle	Δ Productietij	Δ Productietijd / Aant	Δ Productietijd / Aantal * Person	CmpltQty tbv tabel	Δ Productietijd / Aantal / Person	1 Persoon	2 Personen	3 Personen	4 Personen	5 Personen	6 Personen	7 Personen	8 Personen	9 Personen	10 Personen

[redacted]

Figure C-1: Overview of the first sheet of the cycle time tool, called "DATA". Data censored due to confidentiality.

C.10.2 Sheet “CT”



[redacted]

Figure C-2: Overview of the second sheet of the cycle time tool, called "CT". Data censored due to confidentiality.

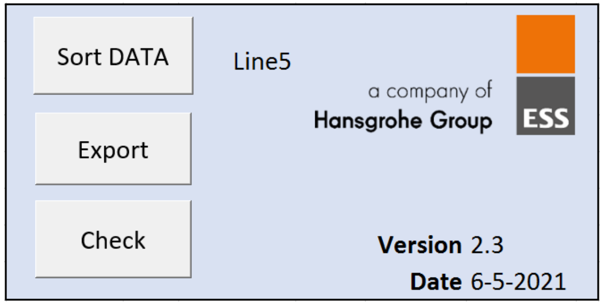


Figure C-3: Control section of the sheet "CT" more detailed.

C.10.3 Sheet "CT2"

Figure C-4: Overview of the third sheet of the cycle time tool, called "CT2". Data censored due to confidentiality.

C.10.4 Sheet "CT3"

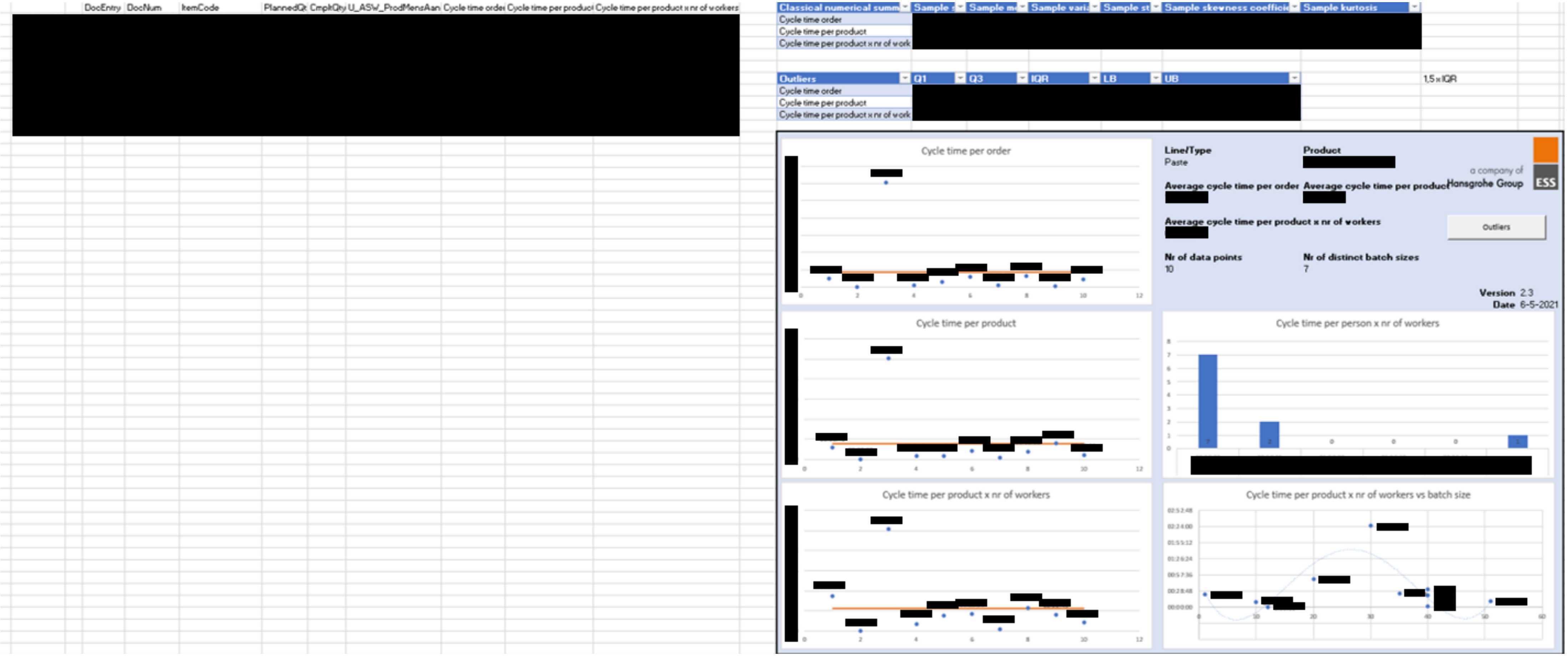


Figure C-5: Overview of the fourth sheet of the cycle time tool, called "CT3". Data censored due to confidentiality.

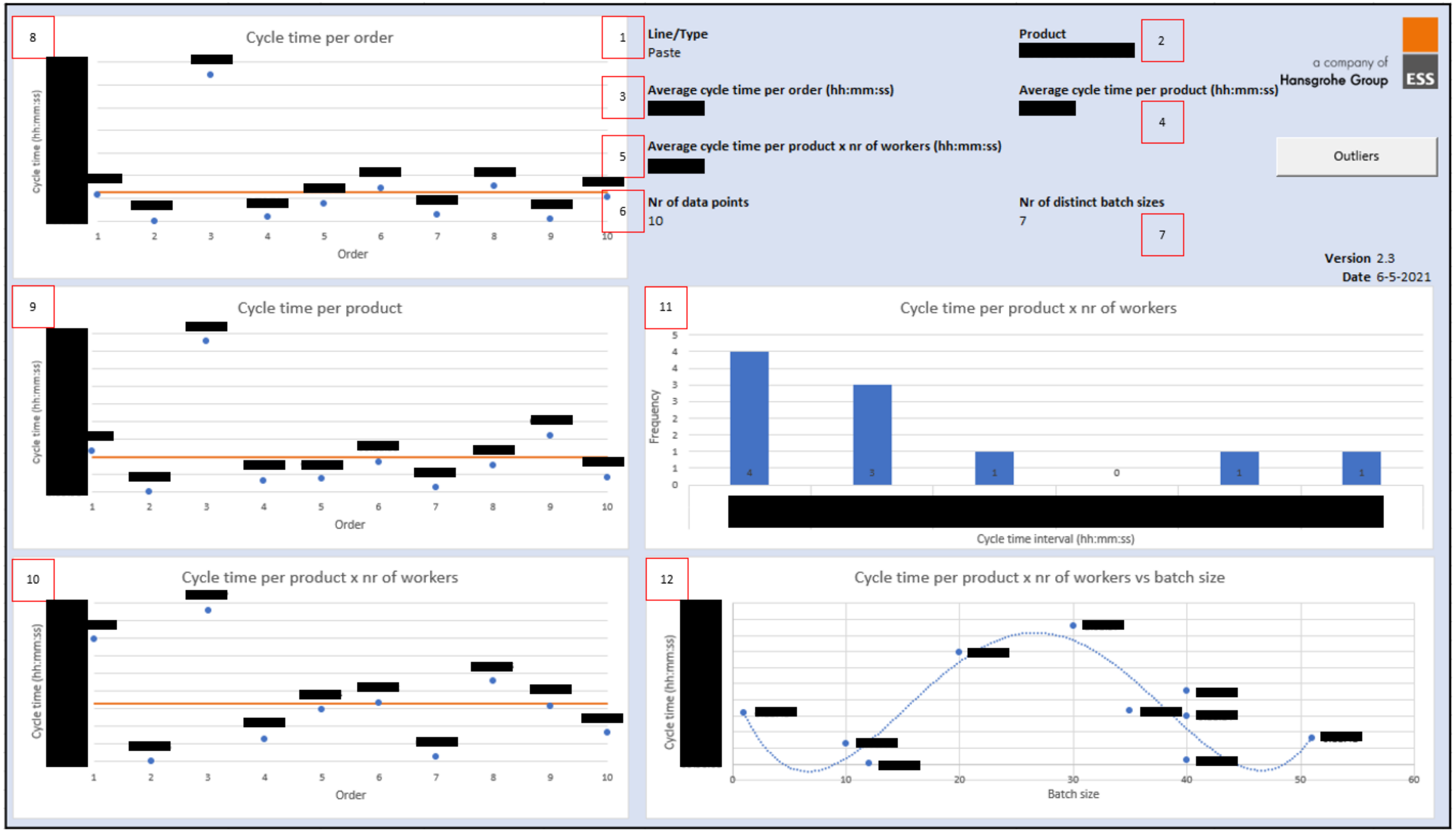


Figure C-6: Dashboard of the sheet "CT3" more detailed (numbers correspond with enumeration in section C.4). Data censored due to confidentiality.

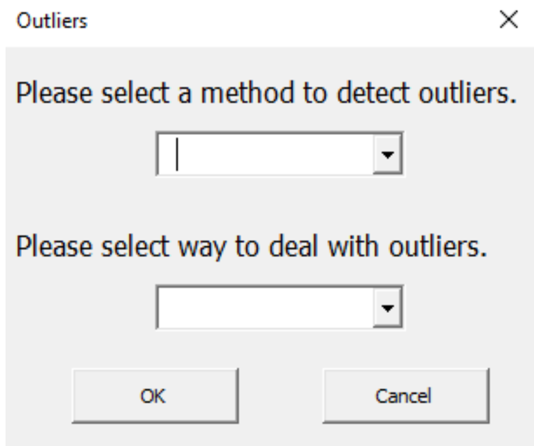


Figure C-7: Pop-up screen that appears after pressing the button "Outliers". The user can select (1) a method to detect and (2)a method to handle outliers.

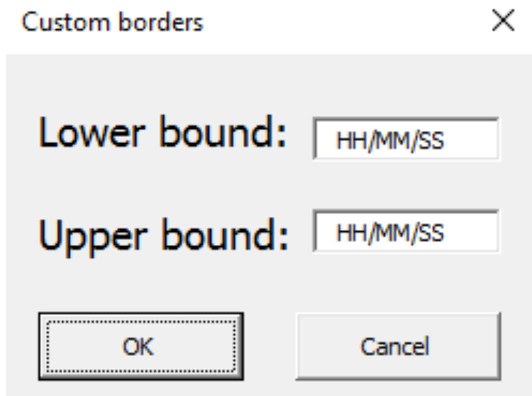


Figure C-8: Pop-up screen that appears after selecting the "Custom borders" option in the pop-up screen depicted above.

C.10.5 Sheet “CT4”

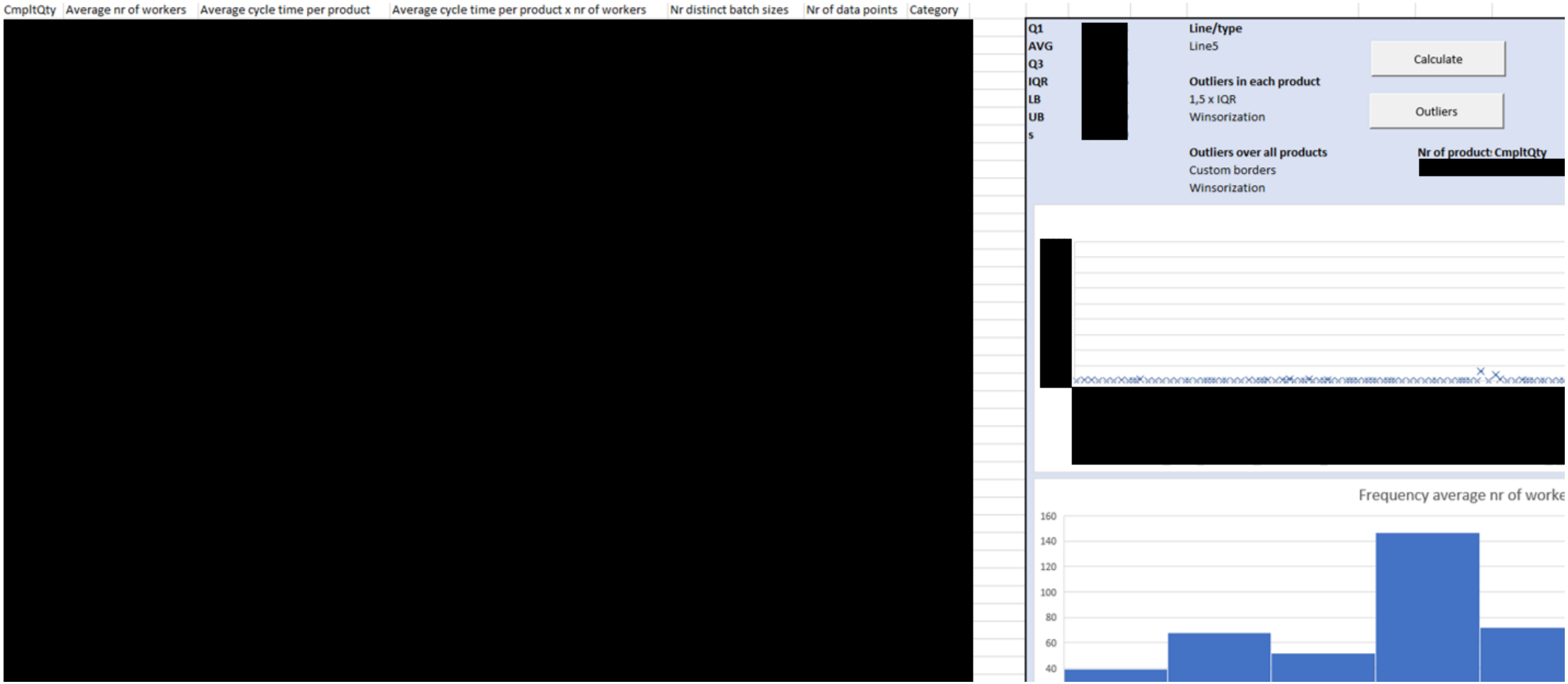


Figure C-9: Overview of the fifth sheet of the cycle time tool, called "CT4". Data censored due to confidentiality.

Figure C-10: Dashboard of the sheet "CT4" more detailed (numbers correspond with enumeration in section C.5). Data censored due to confidentiality.

C.10.6 Sheet “CT5”

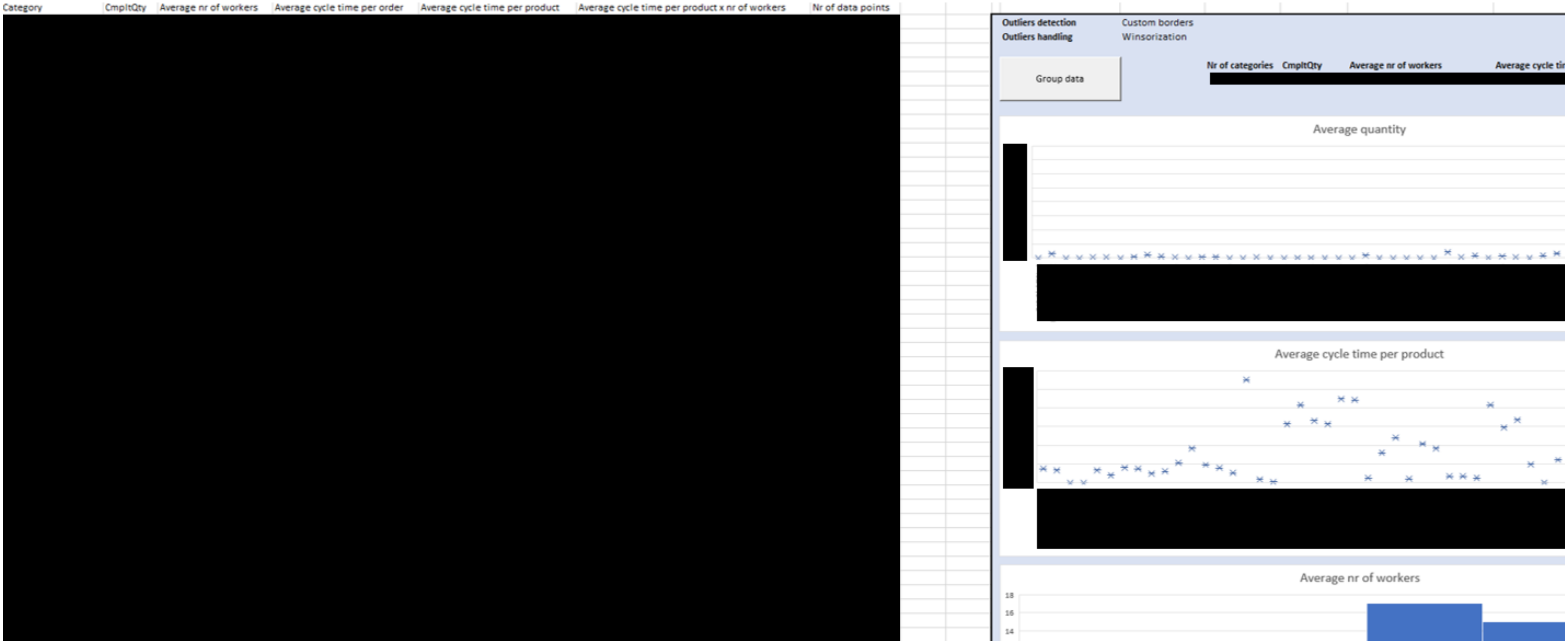


Figure C-11: Overview of the sixth sheet of the cycle time tool, called "CT5". Data censored due to confidentiality.

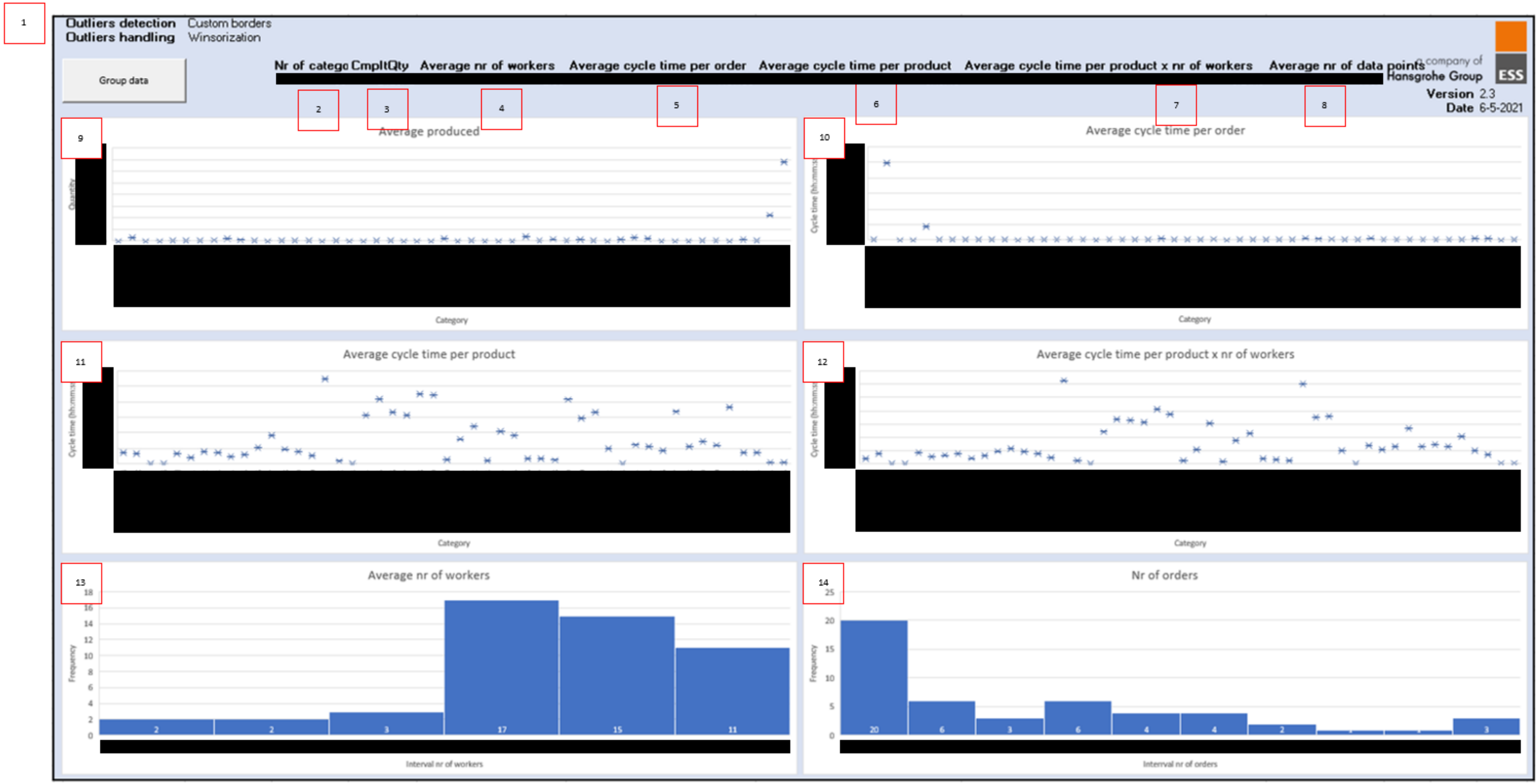


Figure C-12: Dashboard of the sheet "CT5" more detailed. Data censored due to confidentiality.

C.10.7 Sheet "ListOfProducts"

Laser	Paste	Assembly	Tamp	Line 1	Line 2	Line 3	Line 4	Line 5	Category line 5	Line 7	Line 8	Line 9	Line 10

[redacted]

Figure C-13: Overview of the seventh sheet of the cycle time tool, called "ListOfProducts". Data censored due to confidentiality.

C.10.8 Sheet “ListOfProducts2”

Line 1		Line 2		Line 3		Line 4		Line 5		Line 6		Line 7		Line 8		Line 9		Line 10	
Productnummer	Documentnumr	Productnummer	Documentnumr	Productnumme	Documentnumr	Productnummer	Documentnumr	Productnummer	Documentnumr	Productnumr	Documentnumr	Productnummer	Documentnumr	Productnummer	Documentnumr	Productnummer	Documentnumr	Productnummer	Documentnum

[redacted]

Figure C-14: Overview of the eighth sheet of the cycle time tool, called "ListOfProducts2". Data censored due to confidentiality.

C.10.9 Sheet “Validation”

Tamp		None	None
Laser		Custom borders	Trimming
Paste		1,5 x IQR	Winsorization
Assembly		3 x IQR	
Line1		3 x s	
Line2			
Line3			
Line4			
Line5			
Line7			
Line8			
Line9			
Line10			

Figure C-15: Overview of the ninth sheet of the cycle time tool, called "Validation".

C.11 Results

C.11.1 Laser

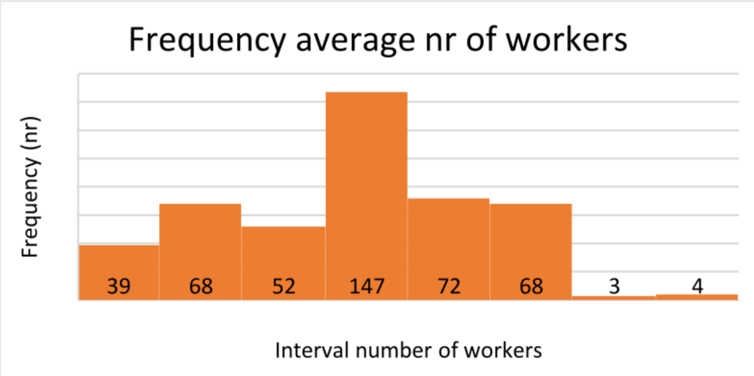


Figure C-16: Frequency of the average number of workers that have helped producing an order in an interval of 0.5 (over all laser products of line 5). Chart axis removed due to confidentiality.

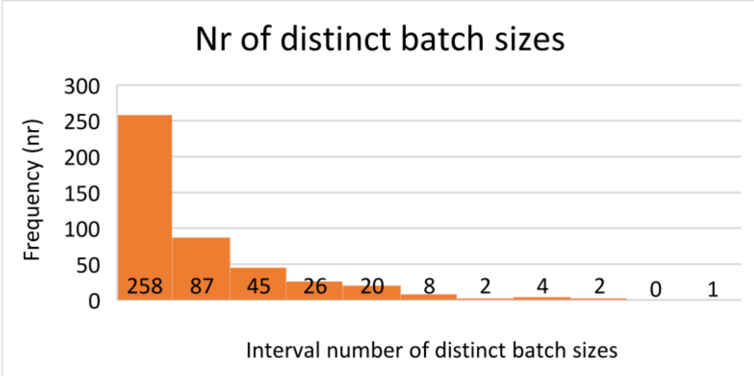


Figure C-17: Frequency of the number of distinct batch sizes per semi-finished product (over all laser products of line 5). Chart axis removed due to confidentiality.

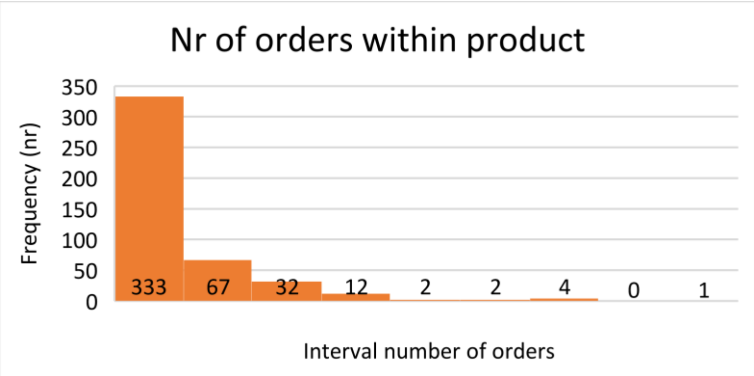


Figure C-18: Frequency of the number of orders per semi-finished products (over all laser products of line 5). Chart axis removed due to confidentiality.

Table C-1: Overview of the measures calculated on the dashboard (over all laser products of line 5). Data censored due to confidentiality.

Nr of products	Average quantity	Average nr of workers	Average cycle time per product (hh:mm:ss)
[redacted]	[redacted]	[redacted]	[redacted]

Average cycle time per product x nr of workers (hh:mm:ss)	Average nr distinct batch sizes	Average nr of data points
[redacted]	[redacted]	[redacted]

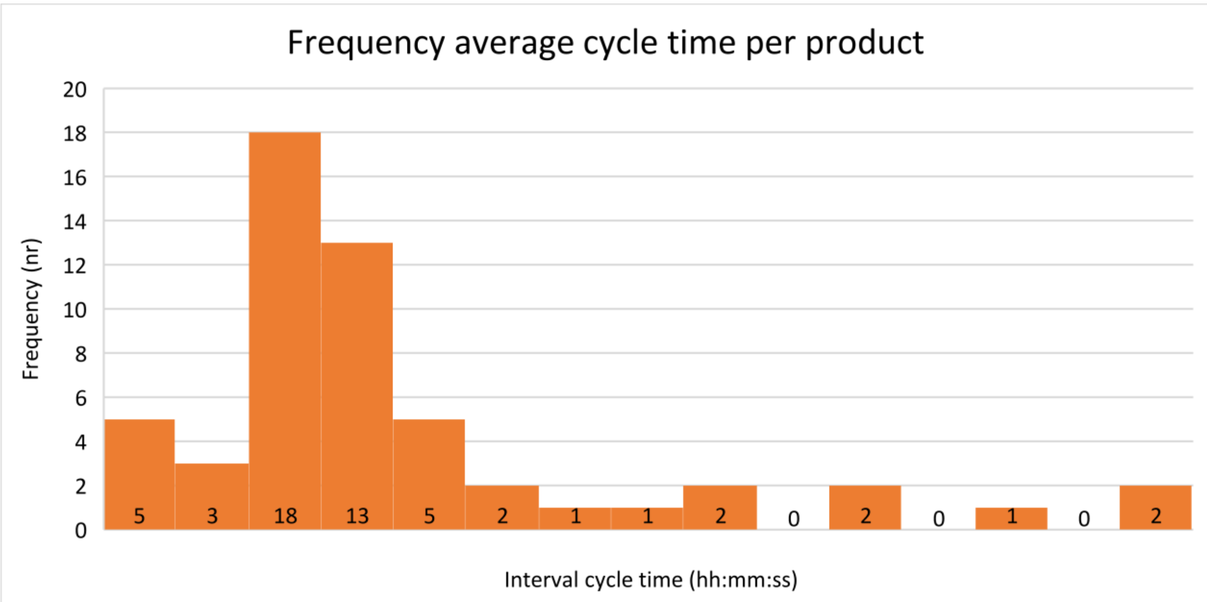


Figure C-19: Frequency of the cycle times per semi-finished products per interval (over all laser products of line 5). Chart axis with cycle times removed due to confidentiality.

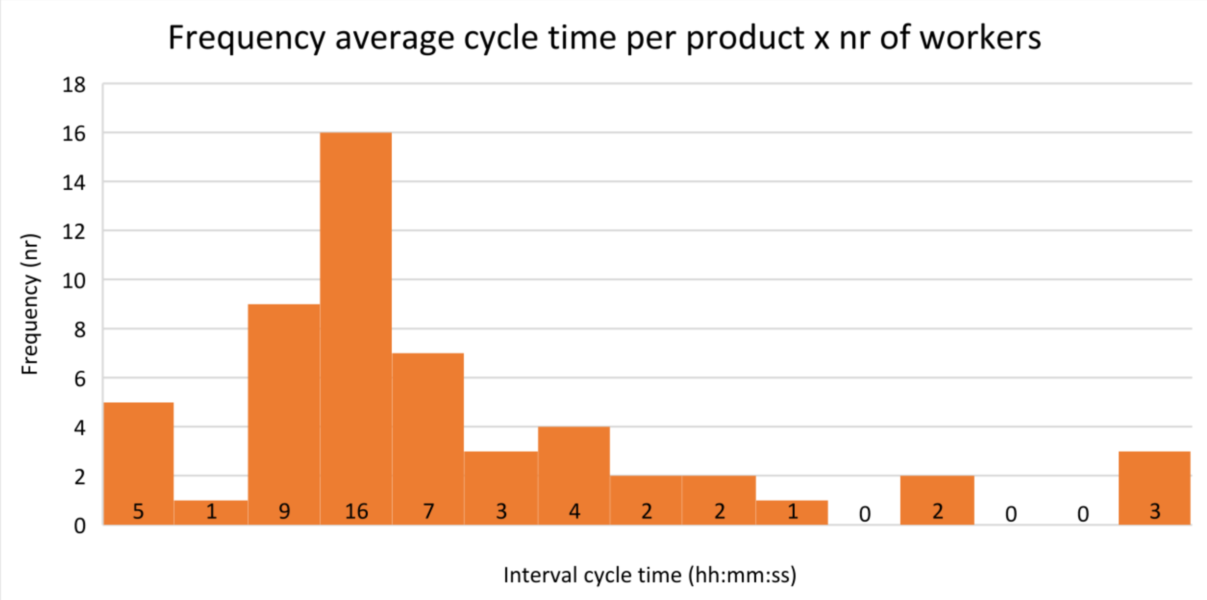


Figure C-20: Frequency of the cycle times per semi-finished products multiplied with the number of workers per interval (over all laser products of line 5). Chart axis with cycle times removed due to confidentiality.

C.11.2 Paste

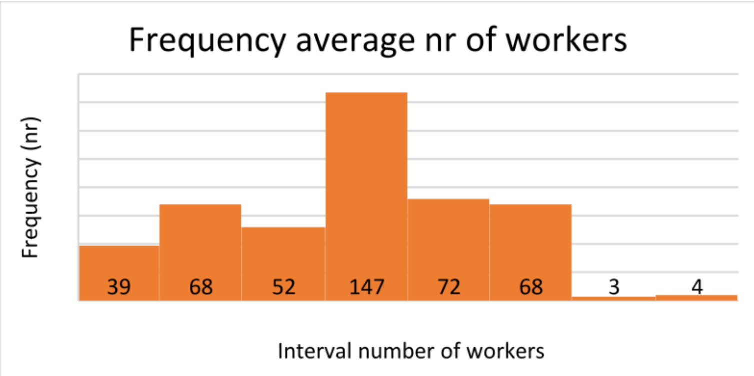


Figure C-21: Frequency of the average number of workers that have helped producing an order in an interval of 0.5 (over all paste products of line 5). Chart axis removed due to confidentiality.

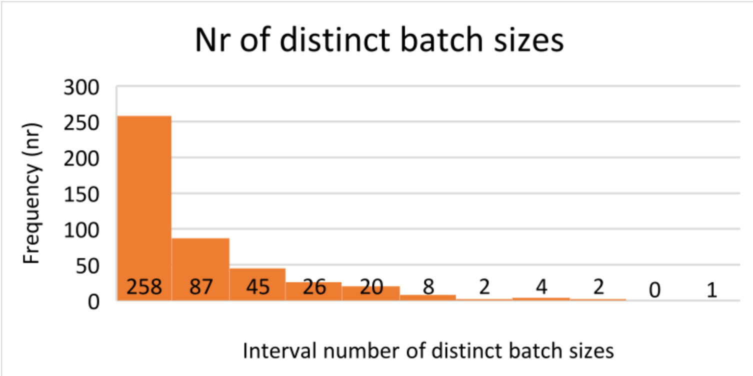


Figure C-22: Frequency of the number of distinct batch sizes per semi-finished product (over all paste products of line 5). Chart axis removed due to confidentiality.

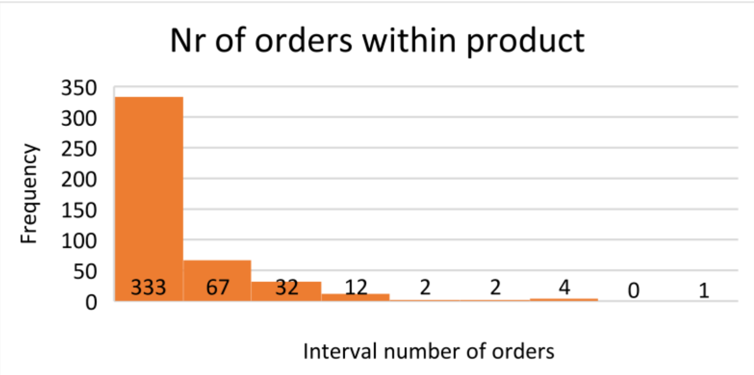


Figure C-23: Frequency of the number of orders per semi-finished products (over all paste products of line 5). Chart axis removed due to confidentiality.

Table C-2: Overview of the measures calculated on the dashboard (over all paste products of line 5). Data censored due to confidentiality.

Nr of products	Average quantity	Average nr of workers	Average cycle time per product (hh:mm:ss)
[redacted]	[redacted]	[redacted]	[redacted]

Average cycle time per product x nr of workers (hh:mm:ss)	Average nr distinct batch sizes	Average nr of data points
[redacted]	[redacted]	[redacted]

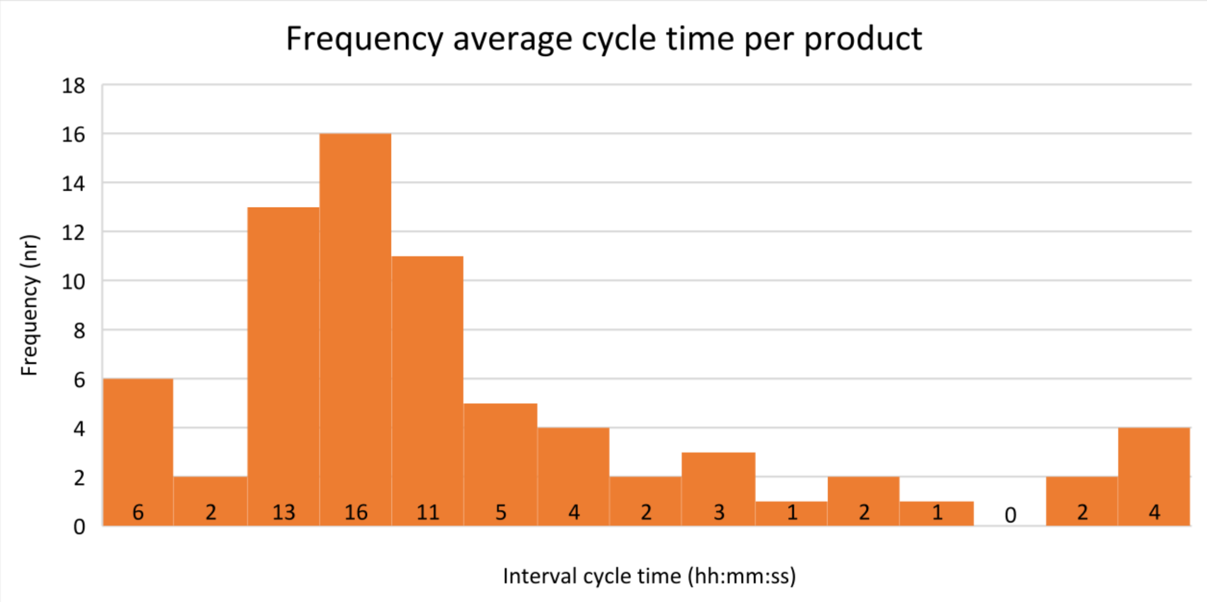


Figure C-24: Frequency of the cycle times per semi-finished products per interval (over all paste products of line 5). Chart axis with cycle times removed due to confidentiality.

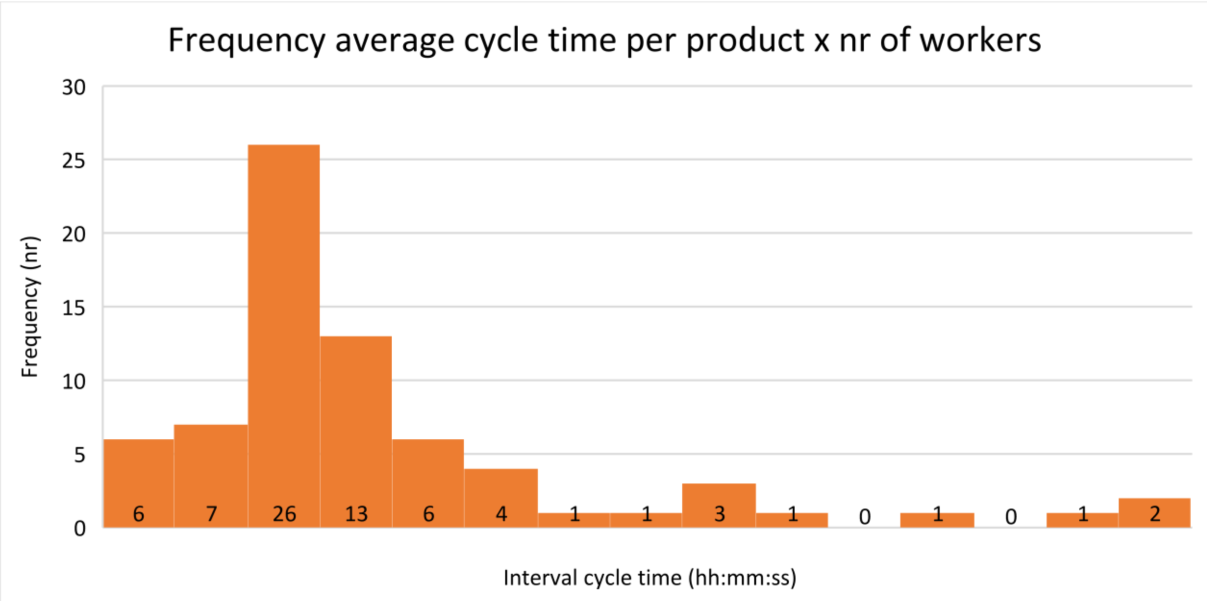


Figure C-25: Frequency of the cycle times per semi-finished products multiplied with the number of workers per interval (over all paste products of line 5). Chart axis with cycle times removed due to confidentiality.

C.11.3 Assembly

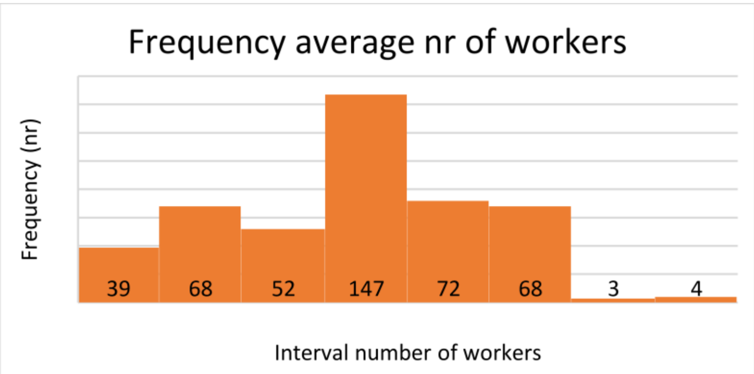


Figure C-26: Frequency of the average number of workers that have helped producing an order in an interval of 0.5 (over all paste products of line 5). Chart axis removed due to confidentiality.

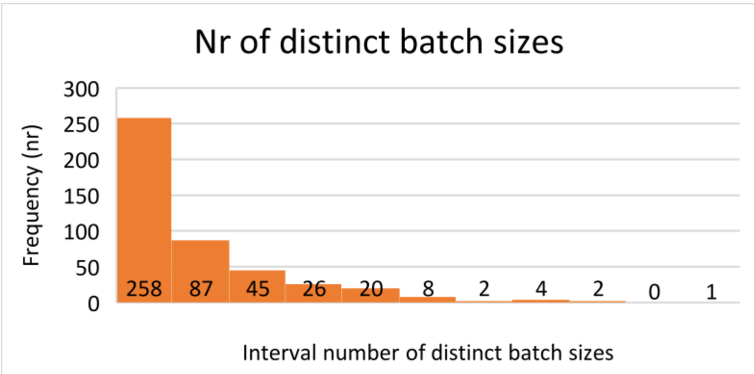


Figure C-27: Frequency of the number of distinct batch sizes per semi-finished product (over all assembly products of line 5). Chart axis removed due to confidentiality.

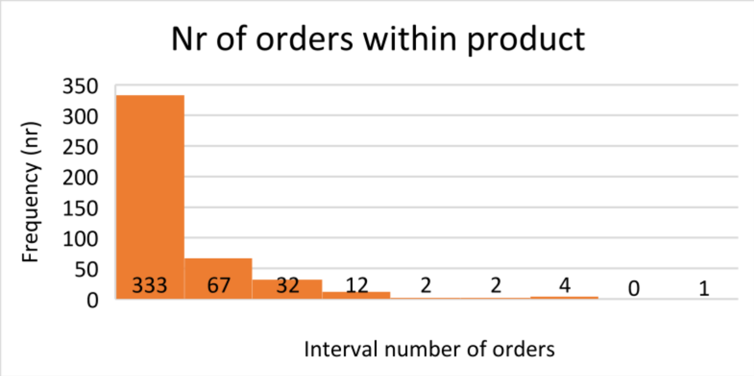


Figure C-28: Frequency of the average number of workers that have helped producing an order per interval of 0,5 (over all assembly orders of line 5). Chart axis removed due to confidentiality.

Table C-3: Overview of the measures calculated on the dashboard (over all assembly products of line 5). Data censored due to confidentiality.

Nr of products	Average quantity	Average nr of workers	Average cycle time per product (hh:mm:ss)
[redacted]	[redacted]	[redacted]	[redacted]

Average cycle time per product x nr of workers (hh:mm:ss)	Average nr distinct batch sizes	Average nr of data points
[redacted]	[redacted]	[redacted]

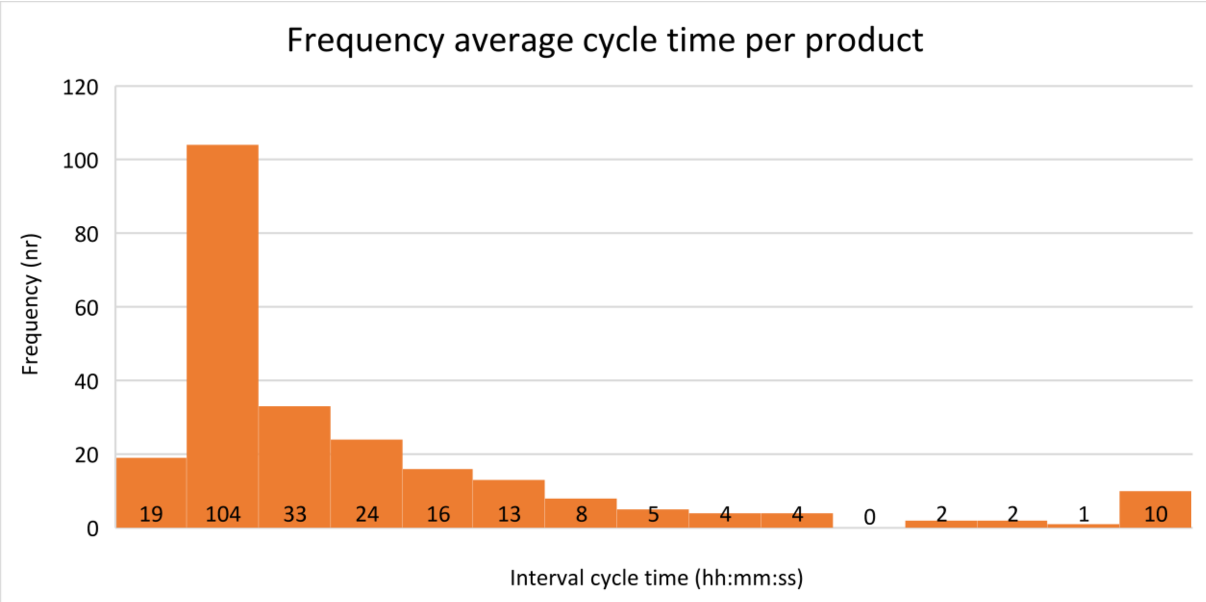


Figure C-29: Frequency of the cycle times per semi-finished products per interval (over all assembly products of line 5). Chart axis with cycle times removed due to confidentiality.

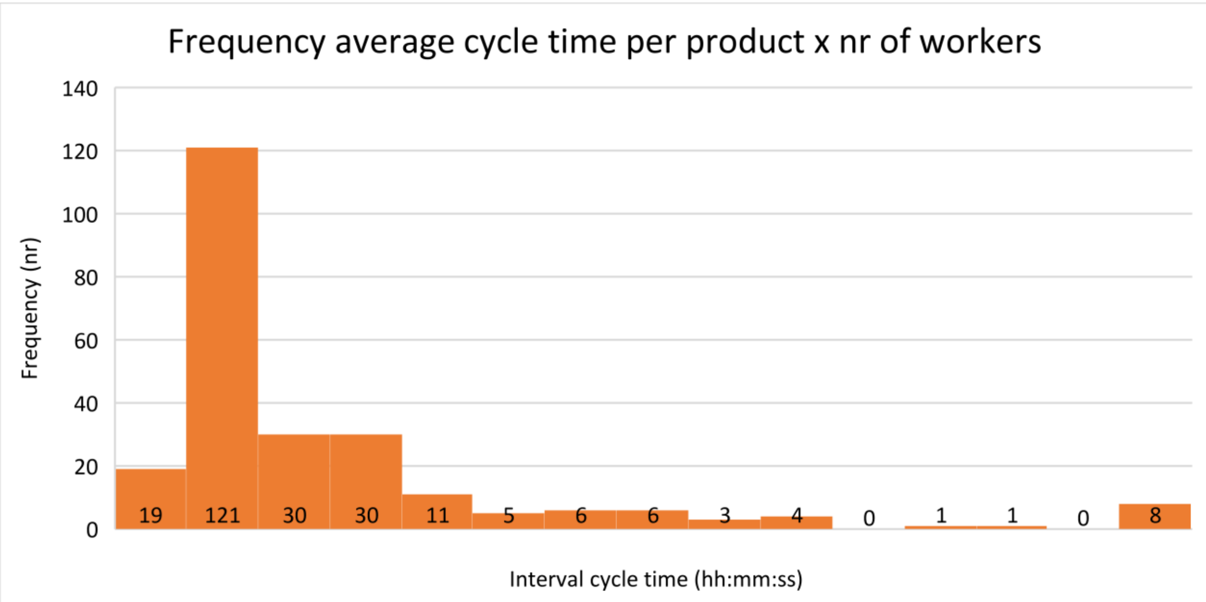


Figure C-30: Frequency of the cycle times per semi-finished products multiplied with the number of workers per interval (over all assembly products of line 5). Chart axis with cycle times removed due to confidentiality.

D. Batch size determination

This appendix contains extra information and tables used during the determination of batch sizes. Section D.1 provides an overview of the products and orders of which the batch sizes are determined. Section D.2 contains the measurements for the laser times. Next, Section D.3 contains the purchase quantities and stock of the non-bulk components. Information regarding the finished goods warehouse is provided in Section D.4. Next, Section D.5 provides an overview of the stock and (forecasted) demand for the finished products. Section D.6 provides an overview of the concluded optimal batch sizes per factor. Section D.7 concludes this appendix and provides an overview of the changes in batch sizes and cycle times and calculations during the sensitivity analysis.

D.1 Overview products

Table 23: Overview of all products and order types for which the batch sizes are determined. All products and order types per group are aggregated in order to have more data and be able to draw a better conclusion (names anonymized).

Product	Laser	Paste	Assembly
Basic			
Basic-1	LaserBasic-1	PlakBasic-1	Basic-1
Basic-2		PlakBasic-2	Basic-2
Basic-3	LaserBasic-3	PlakBasic-3	Basic-3
Basic-4		PlakBasic-4	Basic-4
Simple			
Simple-1-Small			Simple-1-Small
Simple-1-Medium			Simple-1-Medium
Simple-1-Large			Simple-1-Large
Simple-2-Small			Simple-2-Small
Simple-2-Medium			Simple-2-Medium
Simple-2-Large			Simple-2-Large
Simple-3-Small			Simple-3-Small
Simple-3-Medium			Simple-3-Medium
Simple-3-Large			Simple-3-Large
Simple-4-Small			Simple-4-Small
Simple-4-Medium			Simple-4-Medium
Simple-4-Large			Simple-4-Large
Medium			
Medium-1-Small		PlakMedium-1-Small	Medium-1-Small
Medium-2-Small		PlakMedium-2-Small	Medium-2-Small
Medium-3-Small		PlakMedium-3-Small	Medium-3-Small
Medium-4-Small		PlakMedium-4-Small	Medium-4-Small
Medium-1-Medium		PlakMedium-1-Medium	Medium-1-Medium
Medium-2-Medium		PlakMedium-2-Medium	Medium-2-Medium
Medium-3-Medium		PlakMedium-3-Medium	Medium-3-Medium
Medium-4-Medium		PlakMedium-4-Medium	Medium-4-Medium
Medium-1-Large		PlakMedium-1-Large	Medium-1-Large
Medium-2-Large		PlakMedium-2-Large	Medium-2-Large
Medium-3-Large		PlakMedium-3-Large	Medium-3-Large
Medium-4-Large		PlakMedium-4-Large	Medium-4-Large
Difficult			
Difficult-1-Small			Difficult-1-Small
Difficult-2-Small			Difficult-2-Small
Difficult-3-Small			Difficult-3-Small
Difficult-4-Small			Difficult-4-Small
Difficult-1-Medium			Difficult-1-Medium
Difficult-2-Medium			Difficult-2-Medium
Difficult-3-Medium			Difficult-3-Medium
Difficult-4-Medium			Difficult-4-Medium
Difficult-1-Large			Difficult-1-Large
Difficult-2-Large			Difficult-2-Large
Difficult-3-Large			Difficult-3-Large
Difficult-4-Large			Difficult-4-Large

D.2 Laser times

Table 24: Overview of the measurements of the laser order of the basic group.

Measurement	Removing foil time	Laser time	Measurement	Removing foil time	Laser time
1	13.8	6.8	**16**	10.2	7.1
2	10.3	5.9	**17**	11.8	6.7
3	12.9	6.1	**18**	13.8	8.4
4	13.7	6.1	**19**	10.6	7.5
5	9.2	6.8	**20**	15.1	7.0
6	10.4	6.5	**21**	16.3	8.2
7	9.8	8.1	**22**	15.4	8.4
8	7.7	7.6	**23**	10.2	6.4
9	8.1	7.7	**24**	9.3	5.8
10	9.9	5.8	**25**	9.2	5.7
11	12.4	7.0	**26**	10.5	8.6
12	14.2	6.7	**27**	9.7	5.3
13	17.6	7.6	**28**	15.0	6.8
14	15.9	9.1	**29**	14.9	8.5
15	15.1	7.2	**30**	10.2	7.1
Average		Removing foil time	12.2	Laser time	7.1

D.3 Purchase quantities & stock

Table 25: Overview of the purchase quantities and stock of non-bulk components of the basic group.

Component \ Measure	Stock (80%)	Basic-1/3	Basic-2/4	Min order q	Max order q	Fixed order q
Basic-Comp A	765 (612)	1	0	200	0	0
Basic-Comp B	2117 (1694)	1	1	1200	0	0
Basic-Comp C	3617 (2894)	2	2	2000	0	0
Basic-Comp D	3048 (2439)	1	1	1100	0	0
Basic-Comp E	2123 (1699)	1	1	3096	0	0
Basic-Comp F	246 (197)	0	1	200	0	0

Table 26: Overview of the purchase quantities of non-bulk components of the simple group.

	Stock (80%)	Simple-1-Small	Simple-1-Medium	Simple-1-Large	Simple-2-Small	Simple-2-Medium	Simple-2-Large	Simple-3-Small	Simple-3-Medium	Simple-3-Large	Simple-4-Small	Simple-4-Medium	Simple-4-Large	Min order q	Max order q	Fixed order q
Simple-Comp A	83 (67)	0	1	0	0	0	0	0	0	0	0	0	0	100	0	0
Simple-Comp B	2145 (1716)	2	2	2	2	2	2	2	2	2	2	2	2	1	Order q varies between 1000, 1500 en 2000.	
Simple-Comp C	2292 (1834)	0	1	0	0	1	0	0	1	0	0	1	0	540	0	0
Simple-Comp D	3048 (2439)	1	1	0	1	1	0	1	1	0	1	1	0	3000	0	0
Simple-Comp E	2474 (1980)	1	1	0	1	1	0	1	1	0	1	1	0	3000	0	0
Simple-Comp F	10170 (8136)	2	2	3	2	2	3	2	2	3	2	2	3	4000	0	0
Simple-Comp H	102 (82)	0	0	1	0	0	0	0	0	0	0	0	0	200	0	0
Simple-Comp I	1022 (818)	0	0	1	0	0	1	0	0	1	0	0	1	756	0	0
Simple-Comp J	947 (758)	0	0	1	0	0	1	0	0	1	0	0	1	500	0	0
Simple-Comp K	515 (412)	0	0	1	0	0	1	0	0	1	0	0	1	500	0	0
Simple-Comp L	54 (44)	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0
Simple-Comp M	1 (1)	0	0	0	1	0	0	1	0	0	1	0	0	500	0	0
Simple-Comp N	40 (32)	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0
Simple-Comp O	68 (55)	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0
Simple-Comp P	11 (9)	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0
Simple-Comp Q	3 (2)	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0
Simple-Comp R	4 (3)	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0
Simple-Comp S	122 (98)	0	0	0	0	0	0	0	0	0	1	0	0	200	0	0
Simple-Comp T	166 (133)	0	0	0	0	0	0	0	0	0	0	1	0	300	0	0
Simple-Comp U	62 (50)	0	0	0	0	0	0	0	0	0	0	0	1	200	0	0
Simple-Comp V	0 (0)	1	0	0	0	0	0	0	0	0	0	0	0	200	0	0
Simple-Comp W	42 (34)	1	0	0	0	0	0	0	0	0	0	0	0	500	0	0

Table 27: Overview of the purchase quantities of non-bulk components of the medium group.

	Stock (80%)	Stock2 (80%)	Medium-1-Small	Medium-2-Small	Medium-3-Small	Medium-4-Small	Medium-1-Medium	Medium-2-Medium	Medium-3-Medium	Medium-4-Medium	Medium-1-Large	Medium-2-Large	Medium-3-Large	Medium-4-Large	Min order q	Max order q	Fixed order q
Simple-Comp C	2292 (1834)		0	0	0	0	1	1	1	1	0	0	0	0	540	0	0
Simple-Comp D	3048 (2439)		1	1	1	1	1	1	1	1	0	0	0	0	3000	0	0
Simple-Comp E	2474 (1980)		1	1	1	1	1	1	1	1	0	0	0	0	3000	0	0
Simple-Comp I	1022 (818)		0	0	0	0	0	0	0	0	1	1	1	1	756	0	0
Simple-Comp J	947 (758)		0	0	0	0	0	0	0	0	1	1	1	1	500	0	0
Simple-Comp K	515 (412)		0	0	0	0	0	0	0	0	1	1	1	1	500	0	0
Simple-Comp M	1 (1)		1	1	1	1	0	0	0	0	0	0	0	0	500	0	0
Medium-Comp A	20 (16)	27 (22)	1	1	1	1	0	0	0	0	0	0	0	0	50	0	0
Medium-Comp B	0 (0)	22 (18)	1	1	1	1	0	0	0	0	0	0	0	0	30	0	0
Medium-Comp C	49 (40)	122 (98)	0	0	0	0	1	1	1	1	0	0	0	0	100	0	0
Medium-Comp D	0 (0)	20 (16)	0	0	0	0	1	1	1	1	0	0	0	0	50	0	0
Medium-Comp E	31 (25)	65 (52)	0	0	0	0	0	0	0	0	1	1	1	1	100	0	0
Medium-Comp F	0 (0)	39 (32)	0	0	0	0	0	0	0	0	1	1	1	1	50	0	0

Table 28: Overview of the purchase quantities of non-bulk components of the difficult group.

	Stock (80%)	Stock2 (80%)	Difficult-1-Small	Difficult-2-Small	Difficult-3-Small	Difficult-4-Small	Difficult-1-Medium	Difficult-2-Medium	Difficult-3-Medium	Difficult-4-Medium	Difficult-1-Large	Difficult-2-Large	Difficult-3-Large	Difficult-4-Large	Min order q	Max order q	Fixed order q
Simple-Comp A	83 (67)		0	0	0	0	1	0	0	0	0	0	0	0	100	0	0
Simple-Comp C	2292 (1834)		0	0	0	0	1	1	1	1	0	0	0	0	540	0	0
Simple-Comp D	3048 (2439)		1	1	1	1	1	1	1	1	0	0	0	0	3000	0	0
Simple-Comp E	2474 (1980)		1	1	1	1	1	1	1	1	0	0	0	0	3000	0	0
Simple-Comp H	102 (82)		0	0	0	0	0	0	0	0	1	0	0	0	200	0	0
Simple-Comp I	1022 (818)		0	0	0	0	0	0	0	0	1	1	1	1	756	0	0
Simple-Comp J	947 (758)		0	0	0	0	0	0	0	0	1	1	1	1	500	0	0
Simple-Comp K	515 (412)		0	0	0	0	0	0	0	0	1	1	1	1	500	0	0
Simple-Comp L	54 (44)		0	1	0	0	0	0	0	0	0	0	0	0	1	0	0
Simple-Comp N	40 (32)		0	0	0	0	0	1	0	0	0	0	0	0	1	0	0
Simple-Comp O	68 (55)		0	0	0	0	0	0	0	0	0	1	0	0	1	0	0
Simple-Comp P	11 (9)		0	0	1	0	0	0	0	0	0	0	0	0	1	0	0
Simple-Comp R	4 (3)		0	0	0	0	0	0	0	0	0	0	1	0	1	0	0
Simple-Comp S	122 (98)		0	0	0	1	0	0	0	0	0	0	0	0	200	0	0
Simple-Comp T	166 (166)		0	0	0	0	0	0	0	1	0	0	0	0	300	0	0
Simple-Comp U	62 (50)		0	0	0	0	0	0	0	0	0	0	0	1	200	0	0
Simple-Comp V	0 (0)	0	1	0	0	0	0	0	0	0	0	0	0	0	200	0	0
Simple-Comp W	42 (34)	0	1	1	1	1	0	0	0	0	0	0	0	0	500	0	0
Difficult-Comp A	78 (63)	34 (28)	1	1	1	1	0	0	0	0	0	0	0	0	50	0	0
Difficult-Comp B	166 (33)	24 (20)	0	0	0	0	1	1	1	1	0	0	0	0	50	0	0
Difficult-Comp C	65 (52)	51 (41)	0	0	0	0	0	0	0	0	1	1	1	1	50	0	0

D.4 Finished goods warehouse

Table 29: Overview of the information regarding the finished goods warehouse for all products of the groups (names anonymized).

Product	Pallet type	Products per layer	Products per pallet	Number of pallets in warehouse	Comments
Basic-1/2	Euro pallet	4	40	1 (max 2)	Larger quantities possible, as these are stored only shortly.
Basic-3/4					X
Simple-X-Small	Euro pallet	9	117	1	X
Simple-X-Medium		4	48	1	
Simple-X-Large		4	36	1	
Medium-X-Small	Collective storage buck	X	5-6	X	Per variant, 5-6 are possible to store on collective storage bucks.
Medium-X-Medium					
Medium-X-Large					
Difficult-X-Small	Collective storage buck	X	5-6	X	Per variant, 5-6 are possible to store on collective storage bucks.
Difficult-X-Medium					
Difficult-X-Large					

D.5 Stock and (forecasted) demand

Table 30: Overview of the stock, demand and forecasted demand per product. Names anonymized and data censored due to confidentiality.

	Demand			Forecasted demand	
Product	**2019**	**2020**	**2021 (till June)**	**Monthly**	**Yearly**
Basic-1	[redacted]				
Basic-2					
Basic-3					
Basic-4					
Simple-1-Small					
Simple-2-Small					
Simple-3-Small					
Simple-4-Small					
Simple-1-Medium					
Simple-2-Medium					
Simple-3-Medium					
Simple-4-Medium					
Simple-1-Large					
Simple-2-Large					
Simple-3-Large			Censored		
Simple-4-Large					
Medium-1-Small					
Medium-1-Medium					
Medium-1-Large					
Medium-2-Small					
Medium-2-Medium					
Medium-2-Large					
Medium-3-Small					
Medium-3-Medium					
Medium-3-Large					
Medium-4-Small					
Medium-4-Medium					
Medium-4-Large					
Difficult-1-Small					
Difficult-1-Medium					
Difficult-1-Large					
Difficult-2-Small					
Difficult-2-Medium					
Difficult-2-Large					
Difficult-3-Small					
Difficult-3-Medium					
Difficult-3-Large					
Difficult-4-Small					
Difficult-4-Medium					
Difficult-4-Large					

D.6 Conclusion batch sizes

Table 31: Overview of the batch sizes feasible for each factor, including conclusion (names anonymized).

<table>
<tr><th>Factor \ Product group</th><th>Basic</th><th>Simple</th><th>Medium</th><th>Difficult</th></tr>
<tr><td>Station cycle time – laser</td><td>X</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>Station cycle time – paste</td><td>60+</td><td>X</td><td>++</td><td>X</td></tr>
<tr><td>Station cycle time – assembly</td><td>75-200</td><td>0-2 OR 18-40</td><td>++</td><td>2-6</td></tr>
<tr><td>Goods receipt – unloading</td><td colspan="4">++</td></tr>
<tr><td>Goods receipt – booking</td><td colspan="4">++</td></tr>
<tr><td>Purchase</td><td>++ and umber divisible by 20, increments of 20</td><td>++ and number divisible by 10, increments of 10</td><td>++ and number divisible by 10, increments of 10</td><td>++ and number divisible by 10, increments of 10</td></tr>
<tr><td>Components</td><td>Basic-1/3: max 600
Basic-2/3: max 200</td><td>Variant 1: max 70
Variant 2: max 40
Variant 3: max 5
Variant 4: max 80</td><td>Small: max 15
Medium: max 15
Large: max 30</td><td>Max 10</td></tr>
<tr><td>Picking</td><td colspan="4">5+</td></tr>
<tr><td>Finished goods warehouse</td><td>Basic-1/2: ∞, increments of 4
Basic-3/4: max 40/80, increments of 4</td><td>Small: max 117, increments of 9
Medium: max 48, increments of 4
Large: max 36, increments of 4</td><td>Per variant per dimension: max 5-6, no fixed increments</td><td>Per variant per dimension: max 5-6, no fixed increments</td></tr>
<tr><td>Sales</td><td>Basic-1: ±200
Basic-3: ±45
Basic-2: ±30
Basic-4: ±15</td><td>Small (except variant 3 and 2): ±7
Small variant 2: ±11
Small variant 3: ±2
Medium (except variant 3): ±27
Medium variant 3: ±3
Large (except variant 3 and 4): ±18
Large variant 4: ±22
Large variant 3: ±3</td><td>All (except medium and large of variant 1 and 4 and large variant 2): ±1
Medium variant 1: ±8
Large variant 1: ±3
Large variant 2±2
Medium variant 4: ±15
Large variant 4: ±7</td><td><table><tr><td></td><td>1</td><td>2</td><td>3</td><td>4</td></tr><tr><td>Small</td><td>2</td><td>3</td><td>1</td><td>1</td></tr><tr><td>Medium</td><td>5</td><td>8</td><td>2</td><td>9</td></tr><tr><td>Large</td><td>4</td><td>5</td><td>1</td><td>3</td></tr></table></td></tr>
<tr><td colspan="5"></td></tr>
<tr><td>Conclusion</td><td>Basic-1 200
Basic-2 30
Basic-3 40
Basic-4 20</td><td>Simple-1-Small 9
Simple-2-Small 11
Simple-3-Small 2
Simple-4-Small 9
Simple-1-Medium 28
Simple-2-Medium 28
Simple-3-Medium 2
Simple-4-Medium 28
Simple-1-Large 18
Simple-2-Large 18
Simple-3-Large 2
Simple-4-Large 24</td><td>Medium-1-Small 1
Medium-1-Medium 8
Medium-1-Large 3
Medium-2-Small 1
Medium-2-Medium 1
Medium-2-Large 2
Medium-3-Small 1
Medium-3-Medium 1
Medium-3-Large 1
Medium-4-Small 1
Medium-4-Medium 15
Medium-4-Large 7</td><td>Difficult-1-Small 2
Difficult-1-Medium 5
Difficult-1-Large 4
Difficult-2-Small 3
Difficult-2-Medium 7
Difficult-2-Large 6
Difficult-3-Small 1
Difficult-3-Medium 2
Difficult-3-Large 1
Difficult-4-Small 1
Difficult-4-Medium 9
Difficult-4-Large 3</td></tr>
<tr><td>Expected decrease</td><td>-10%</td><td>-10%</td><td>-15%</td><td>-20%</td></tr>
<tr><td>Difference cycle time (compared with average)</td><td>-15.4%</td><td>-13.9%</td><td>0.0%</td><td>-19.3%</td></tr>
</table>

D.7 Sensitivity analysis batch sizes

D.7.1 Demand

Table 32: Overview for the differences in batch sizes (BS), cycle times (CT) and cycle time per group (CT group) for demand analysis as part of the sensitivity analysis (names anonymized).

	5%			10%			20%		
Product	**Δ BS**	**Δ CT**	**Δ CT group**	**Δ BS**	**Δ CT**	**Δ CT group**	**Δ BS**	**Δ CT**	**Δ CT group**
Basic-1	0	0.0%	-15.4%	0	0.0%	-16.3%	20	-3.3%	-4.4%
		0.0%			0.0%			45.2%	
Basic-2	0	0.0%		0	0.0%		2	-1.2%	
		0.0%			0.0%			-5.3%	
Basic-3	0	0.0%		10	-3.9%		10	-3.9%	
		0.0%			-5.3%			-5.3%	
Basic-4	0	0.0%		5	-6.9%		5	-6.9%	
		0.0%			-7.4%			-7.4%	
Simple-1-Small	0	0.0%	-14.9%	0	0.0%	-14.6%	0	0.0%	-15.2%
Simple-2-Small	1	-2.4%		1	-2.4%		2	-9.5%	
Simple-3-Small	0	0.0%		0	0.0%		0	0.0%	
Simple-4-Small	0	0.0%		0	0.0%		0	0.0%	
Simple-1-Medium	0	0.0%		0	0.0%		0	0.0%	
Simple-2-Medium	0	0.0%		0	0.0%		0	0.0%	
Simple-3-Medium	2	95.0%		2	95.0%		2	95.0%	
Simple-4-Medium	4	14.3%		6	14.3%		10	9.5%	
Simple-1-Large	2	-39.5%		2	-39.5%		2	-39.5%	
Simple-2-Large	2	-39.5%		2	-39.5%		2	-39.5%	
Simple-3-Large	2	95.0%		2	95.0%		2	95.0%	
Simple-4-Large	1	9.3%		2	14.8%		4	33.3%	
Medium-1-Small	0	0.0%	-2.2%	0	0.0%	-2.2%	0	0.0%	-2.2%
		0.0%			0.0%			0.0%	
Medium-1-Medium	0	0.0%		0	0.0%		0	0.0%	
		0.0%			0.0%			0.0%	
Medium-1-Large	0	0.0%		0	0.0%		0	0.0%	
		0.0%			0.0%			0.0%	
Medium-2-Small	0	0.0%		0	0.0%		0	0.0%	
		0.0%			0.0%			0.0%	
Medium-2-Medium	0	0.0%		0	0.0%		0	0.0%	
		0.0%			0.0%			0.0%	
Medium-2-Large	0	0.0%		0	0.0%		0	0.0%	
		0.0%			0.0%			0.0%	
Medium-3-Small	0	0.0%		0	0.0%		0	0.0%	
		0.0%			0.0%			0.0%	
Medium-3-Medium	1	-16.7%		1	-16.7%		1	-16.7%	
		-25.0%			-25.0%			-25.0%	
Medium-3-Large	0	0.0%		0	0.0%		0	0.0%	
		0.0%			0.0%			0.0%	
Medium-4-Small	1	-16.7%		1	-16.7%		1	-16.7%	
		-25.0%			-25.0%			-25.0%	
Medium-4-Medium	0	0.0%		0	0.0%		0	0.0%	
		0.0%			0.0%			0.0%	
Medium-4-Large	1	-8.3%		1	-8.3%		1	-8.3%	
		7.1%			7.1%			7.1%	
Difficult-1-Small	0	0.0%	-19.0%	0	0.0%	-20.1%	0	0.0%	-20.4%
Difficult-1-Medium	0	0.0%		1	1.2%		1	1.2%	
Difficult-1-Large	0	0.0%		1	-1.2%		1	-1.2%	
Difficult-2-Small	1	-2.3%		1	-2.3%		1	-2.3%	
Difficult-2-Medium	2	9.8%		2	-0.6%		2	-0.6%	
Difficult-2-Large	0	0.0%		0	0.0%		1	-1.8%	
Difficult-3-Small	0	0.0%		0	0.0%		0	0.0%	
Difficult-3-Medium	0	0.0%		0	0.0%		0	0.0%	
Difficult-3-Large	0	0.0%		0	0.0%		0	0.0%	
Difficult-4-Small	0	0.0%		0	0.0%		0	0.0%	
Difficult-4-Medium	1	-4.3%		1	-4.3%		1	-4.3%	
Difficult-4-Large	0	0.0%		0	0.0%		0	0.0%	

D.7.2 Components

Table 33: Overview for the differences in batch sizes (BS), cycle times (CT) and cycle time per group (CT group) for demand analysis as part of the sensitivity analysis (names anonymized).

	-25%			-50%			-75%		
Product	**Δ BS**	**Δ CT**	**Δ CT group**	**Δ BS**	**Δ CT**	**Δ CT group**	**Δ BS**	**Δ CT**	**Δ CT group**
Basic-1	0	0.0%	-15.4%	0	0.0%	-15.4%	-50	11.1%	-22.0%
		0.0%			0.0%			-32.3%	
Basic-2	0	0.0%		0	0.0%		0	0.0%	
		0.0%			0.0%			0.0%	
Basic-3	0	0.0%		0	0.0%		0	0.0%	
		0.0%			0.0%			0.0%	
Basic-4	0	0.0%		0	0.0%		0	0.0%	
		0.0%			0.0%			0.0%	
Simple-1-Small	0	0.0%	-13.9%	0	0.0%	-15.8%	0	0.0%	21.7%
Simple-2-Small	0	0.0%		0	0.0%		-1	19.0%	
Simple-3-Small	0	0.0%		0	0.0%		-1	-55.0%	
Simple-4-Small	0	0.0%		0	0.0%		0	0.0%	
Simple-1-Medium	0	0.0%		0	0.0%		-11	52.4%	
Simple-2-Medium	0	0.0%		-8	-19.0%		-18	257.1%	
Simple-3-Medium	0	0.0%		0	0.0%		-1	-55.0%	
Simple-4-Medium	0	0.0%		0	0.0%		-8	-19.0%	
Simple-1-Large	0	0.0%		0	0.0%		-1	12.3%	
Simple-2-Large	0	0.0%		0	0.0%		-8	163.2%	
Simple-3-Large	0	0.0%		0	0.0%		-1	-55.0%	
Simple-4-Large	0	0.0%		0	0.0%		-4	25.9%	
Medium-1-Small	0	0.0%	1.9%	0	0.0%	2.9%	0	0.0%	25.4%
		0.0%			0.0%			0.0%	
Medium-1-Medium	0	0.0%		-1	9.1%		-4	78.8%	
		0.0%			-6.7%			60.0%	
Medium-1-Large	0	0.0%		0	0.0%		0	0.0%	
		0.0%			0.0%			0.0%	
Medium-2-Small	0	0.0%		0	0.0%		0	0.0%	
		0.0%			0.0%			0.0%	
Medium-2-Medium	0	0.0%		0	0.0%		0	0.0%	
		0.0%			0.0%			0.0%	
Medium-2-Large	0	0.0%		0	0.0%		0	0.0%	
		0.0%			0.0%			0.0%	
Medium-3-Small	0	0.0%		0	0.0%		0	0.0%	
		0.0%			0.0%			0.0%	
Medium-3-Medium	0	0.0%		0	0.0%		0	0.0%	
		0.0%			0.0%			0.0%	
Medium-3-Large	0	0.0%		0	0.0%		0	0.0%	
		0.0%			0.0%			0.0%	
Medium-4-Small	0	0.0%		0	0.0%		0	0.0%	
		0.0%			0.0%			0.0%	
Medium-4-Medium	-4	8.3%		-8	12.5%		-11	84.4%	
		13.9%			16.7%			100.0%	
Medium-4-Large	0	0.0%		0	0.0%		0	0.0%	
		0.0%			0.0%			0.0%	
Difficult-1-Small	0	0.0%	-19.3%	0	0.0%	-18.6%	0	0.0%	-14.9%
Difficult-1-Medium	0	0.0%		0	0.0%		-3	7.1%	
Difficult-1-Large	0	0.0%		0	0.0%		-2	5.9%	
Difficult-2-Small	0	0.0%		0	0.0%		-1	3.4%	
Difficult-2-Medium	0	0.0%		-2	2.4%		-5	9.8%	
Difficult-2-Large	0	0.0%		-1	0.6%		-4	7.8%	
Difficult-3-Small	0	0.0%		0	0.0%		0	0.0%	
Difficult-3-Medium	0	0.0%		0	0.0%		0	0.0%	
Difficult-3-Large	0	0.0%		0	0.0%		0	0.0%	
Difficult-4-Small	0	0.0%		0	0.0%		0	0.0%	
Difficult-4-Medium	-2	0.6%		-4	3.1%		-7	10.4%	
Difficult-4-Large	0	0.0%		0	0.0%		-1	3.4%	

E. Description quality issues tool

This appendix contains a description of the tool that has been made to give insight in the quality issues tool, called “quality issues tool”. The tool consists of 9 sheets, which are explained in the sections below. The last section, Section E.8, contains screenshots of each sheet. As the language of the data is Dutch (e.g., the reasons), the tool is fully made in Dutch. The explanation in the section below, however, has been written in English, including the Dutch words (between quotation marks in brackets) that can be found in the screenshots.

E.1 Sheet 1: “Retour”

The first sheet of the tool provides data of rejected components and is called “Retour” (see Figure E-1). It contains the data about the quality rejections of components of all lines that is not the consequence of an action of ESS and is, therefore, send back to the supplier. It contains only the rejections of components that are worth sending back: components representing a low value and, as a consequence, not worth sending back are not part of the data. This data is coming from the quality manager, who manually keeps track of all quality issues and reasons using an Excel sheet. The format of this is the same as the sheet the quality manager uses, which makes loading new data easier. The following information is contained in the sheet:

- **Number (“Nummer”)**: the (row) number of the quality issue, started in May 2006;
- **Document number (“Documentnummer”)**: the document number in which the component is rejected because of a quality problem.
- **Customer / Supplier name (“Klant-/leverancierna am”)**: name of the customer or supplier who has received / delivered the component(s);
- **Booking date (“Boekingsdatum”)**: date when the quality issue is booked;
- **Expiration date (“Vervaldatum”)**: date when the quality issue is expired;
- **Component number (“Artikelnummer”)**: distinct number used internally to distinguish between different components;
- **Component / service description (“Artikel-/serviceomschrijving”)**: description of the component.
- **Quantity (“Hoeveelheid”)**: the number of components that is/are rejected because of (a) quality issue(s).
- **Row total (“Regeltotaal”)**:
- **Purchase text (“Inkoop tekst”)**: the reason why the component(s) is/are rejected, which is added since 2019.
- **Comment (“Opmerking”)**: optional comment about the quality issue.

E.2 Sheet 2: “Supplier 1” & Sheet3: “Supplier 2”

The second and third sheets are called “Supplier 1” and “Supplier 2” and are respectively depicted in Figure E-2 and E-3. These sheets contain information about the deliveries of the suppliers Supplier 1 and Supplier 2. As these two suppliers deliver (almost) all components for the container-series line, only the data of these two suppliers is added to the tool. These sheets contain information about all delivered components of Supplier 1 and Supplier 2 for all lines and are extracted from the ERP system. To ease the loading of new data, the layout of these sheets is the same as the extraction from the ERP system. More specifically, each of the sheets contains the following information:

- **Number (“Nummer”)**: the (row) number of the quality issue, depending on the start date of the data (in this case begin 2019).
- **Supplier (“Leverancier”)**: name of the supplier who delivers the component(s);
- **Component number (“Artikelnummer”)**: distinct number used internally to distinguish between different components;

- **Component / service description (“Artikel-/serviceomschrijving”)**: description of the component;
- **Document number (“Documentnummer”)**: the document number (order) in which the component(s) is/are received;
- **Received (“Ontvangen”)**: the quantity of components received from /delivered by the supplier.
- **Booking date (“Boekingsdatum”)**: date when the quality issue is booked.

E.3 Sheet 4: “Retour5”

This sheet is depicted in Figure E-4 and contains the rejections due to quality issues specifically for line 5. As there is no (easy way) to sort out the data for line 5 automatically, the data must be filtered out manually based on the component description using the Excel filter option. Besides, the data before 23-04-19 is filtered and deleted, as the quality manager began adding the reason for quality issues from this data. To analyze the quality issues and reasons, it is important that the reason is added with which the quality manager started at 23-04-19. However, there are still some rejections without a reason, which are given the text “Geen reden” (no reason). After filtering the data manually, the information is copied 1:1 to the sheet “Retour5”. This sheet provides input for the calculations of the other sheets.

As the data is only used internally and not for any (further) analysis, the reasons for the rejection are not standardized. Most of the time, however, the same reasons occur and are listed in the sheet. To be able to analyze the reasons correctly, a set of standardized reasons (twenty-two in total) are identified from the list of all (raw) reasons. Many times, the same reason is given to a quality rejection, but with different wording. By standardizing the reasons, (a) conclusion(s) can be drawn regarding the (frequency of) reasons. By analyzing the reasons manually, I identified the following (standardized) reasons:

1. No reason (“Geen reden”)
2. Damaged (“Beschadigd”)
3. Malfunction (“Defect”)
4. Dent (“Deuk”)
5. No pin (“Geen stift”)
6. Scratches (“Krassen”)
7. Scratches through cutting out foil (“Krassen door uistnijden folie”)
8. Bent (“Krom”)
9. Paint error (“Lakfout”)
10. Welding error (“Lasfout”)
11. Leak (“Lek”)
12. Dimensions (“Maatvoering”)
13. Not ordered (“Niet bested”)
14. Missing part (“Ontbrekend onderdeel”)
15. Production error (“Productiefout”)
16. Dots (“Puntjes”)
17. Sharp angles (“Scherpe hoeken”)
18. Grinding direction (“Slijprichting”)
19. Stains (“Vlekken”)
20. Mounting error (“Zetfout”)
21. Multiple (“Meerdere”)
22. Others (“Overige”)

E.4 Sheet 5: “Supplier 15” & Sheet 6:“Supplier 25”

Overviews of the Sheets “Supplier 15” and “Supplier 25” can be seen in Figures E-5 and E-6. These sheets contain information about the delivery of components by respectively Supplier 1 and Supplier 2 specifically for line 5 and filtered on date.

This information is obtained by manually filtering the information of the sheet Supplier 1/Supplier 2 using the filter option in Excel (based on the column containing the descriptions). Thus must be done manually as there is no (easy) way to filter out the information automatically. Besides, the data before 23-04-19 is deleted to have data of the deliveries from the same period as the data from the quality rejections. This way, the rejections can be compared with the incoming components. The format of “Supplier 15” and “Supplier 25” is the same as the format of the sheets the information is coming from (respectively “Supplier 1” and “Supplier 2”).

The function of the sheets “Supplier 15” and “Supplier 25” is to provide information about the delivery of components for line 5. This number can be compared with the quality rejections from the same period. As Supplier 1 and Supplier 2 (almost) deliver all components for line 5, only these two suppliers are used in this tool.

E.5 Sheet 7: “Artikel”

The sheet called “Artikel” is (one of) the main sheets of the tool and can be seen more detailed in Figure E-7. In the dashboard on the right side of the sheet, the user can select a component via a drop-down menu. By selecting an article, the tool automatically finds and copies all rejections (including additional information) that have been booked in the system (in sheet “Retour5”) in the sheet. Next, the number of times a reason occurs is counted and written to the dashboard. Moreover, the tool calculates the total number of components delivered (from “Supplier 15” or “Supplier 25”). In case there is no rejection or delivery of the component, the words “Geen data” (No data) is written to the sheet. When all rejections and deliveries have been found, the graphs automatically update themselves.

The dashboard on this sheet can be seen more detailed in Figure E-8. The graph types are based on the literature study to the best way of visualizing data (Section 3.2.1). The dashboard contains the following information (numbers corresponds with numbers in Figure E-8):

1. The selected **component (“Artikel nr”)**;
2. The **description** of the component **(“Omschrijving”)**;
3. The **supplier** delivering the component **(“Leverancier”)**;
4. The **total quantity delivered (“Totaal geleverd”)**;
5. The **total quantity rejected** because of a quality issue **(“Totaal afkeur”)**;
6. **Percentage rejection** relative to the total quantity delivered **(“% afkeur”);**
7. The **quantity (“Aantal”), percentage** rejection relative to the **total rejection (“% van afkeur”)** and **percentage** rejection relative to the **total quantity delivered (“% van levering”)** for all reasons;
8. Graph of the **quantity rejected (“Aantal”)**, **cumulative percentage** rejection relative to the **total rejection (“Cumulatief % van afkeur”)** and **cumulative percentage** rejection relative to the **total quantity delivered (“Cumulatief % van levering”)** per reason.
9. Graph of the **percentage non-rejected and rejected components** (split out per reason) relative to the **total quantity delivered**.

E.6 Sheet 8: “Artikelen”

The aim of this sheet is to provide an overview of the number of rejections (per reason) and total number of delivered components for all components. An overview can be seen in Figure E-9. By pressing the button “Load data” on the dashboard, the tool find/calculates and copies the following information to the sheet:

- **Component number (“Artikelnummer”)**: distinct number used internally to distinguish between different components;
- **Component / service description (“Artikel-/serviceomschrijving”)**: description of the component.
- **Customer / Supplier name (“Klant-/leveranciernaam”)**: name of the customer or supplier who has received / delivered the component(s);
- **Total delivered**: the total number of components delivered (since 23-04-19);
- **Total rejected**: the total number of components rejected because of a quality issue (since 23-04-19);
- **Percentage rejection**: the percentage of rejected components against total number delivered;
- **No reason (“Geen reden”)**: the total quantity of a component rejected with no reason given;

- **Damaged (“Beschadigd”)**: the total quantity of a component rejected because of a damage;
- **Malfunction (“Defect”)**: the total quantity of a component rejected because of a malfunction;
- **Dent (“Deuk”)**: the total quantity of a component rejected because of a dent;
- **No pin (“Geen stift”)**: the total quantity of a component rejected because no pin included;
- **Scratches (“Krassen”)**: the total quantity of a component rejected because of scratches;
- **Scratches through cutting out foil (“Krassen door uistnijden folie”)**: the total quantity of a component rejected because scratches through cutting out foil;
- **Bent (“Krom”)**: the total quantity of a component rejected because the component was not straight;
- **Paint error (“Lakfout”)**: the total quantity of a component rejected because of a paint error;
- **Welding error (“Lasfout”)**: the total quantity of a component rejected because of a welding error;
- **Leak (“Lek”)**: the total quantity of a component rejected because the component was leak;
- **Dimensions (“Maatvoering”)**: the total quantity of a component rejected because of wrong dimensions;
- **Not ordered (“Niet besteld”)**: the total quantity of a component rejected because of not ordered;
- **Missing part (“Ontbrekend onderdeel”)**: the total quantity of a component rejected because of missing (a) part of the component;
- **Production error (“Productiefout”)**: the total quantity of a component rejected because of a production error;
- **Dots (“Puntjes”)**: the total quantity of a component rejected because of dots in the component;
- **Sharp angles (“Scherpe hoeken”)**: the total quantity of a component rejected because of sharp angles;
- **Grinding direction (“Slijprichting”)**: the total quantity of a component rejected because of wrong grinding direction;
- **Stains (“Vlekken”)**: the total quantity of a component rejected because of stains;
- **Mounting error (“Zetfout”)**: the total quantity of a component rejected because of a mounting error;
- **Multiple (“Meerdere”)**: the total quantity of a component rejected because of multiple reasons (reasons in comments);
- **Others (“Overige”)**: the total quantity of a component rejected because of other reason(s) (reason(s) in comments);
- **Comments (“Opmerkingen”)**: optional comment about the quality issue.

When all the data is loaded and the sheet is filled, the measures and graphs within the dashboard are updated automatically. The dashboard can be seen more detailed in Figure E-10 and contains the following information (based on literature study of Section 3.2.1):

1. The **total number of different components** in the overview **(“Totaal artikelen”)**;
2. The **total number of components delivered (“Totaal geleverd”)**;
3. The **total number of components rejected** because of a quality issue **(“Totaal afgekeurd”)**;
4. **Percentage total rejection** relative to total delivered **(“% Totaal afgekeurd/total geleverd”)**;
5. **Total different components** delivered by **Supplier 1**;
6. **Total different components** delivered by **Supplier 2**;
7. **Total different components** delivered by **other suppliers**;
8. **Total number of components with no rejection at all (“Artikelen zonder afkeur”)** total (“Totaal”), percentage relative to total number of components (“%”) and per supplier (“Supplier 1” and “Supplier 2”);
9. **Total number of components with rejection (“Artikelen zonder afkeur”)** total (“Totaal”), percentage relative to total number of components (“%”) and per supplier (“Supplier 1” and “Supplier 2”);

10. The **number of different components ("Aantal verschillende artikelen"), total quantity ("Aantal"), percentage** rejection relative to the **total rejection ("% van afkeur")** and **percentage** rejection relative to the **total quantity delivered ("% van levering")** per reason;
11. Graph of the **frequency** with which a **component** is **rejected** per supplier per reason;
12. Histogram of the **frequency of the total rejection percentage** over all components;
13. Graph of the **top ten components** with **highest percentage total rejection**;
14. Pie chart of the **total quantity delivered without rejection and total rejection** (percentage relative to the total quantity delivered) for Supplier 1;
15. Pie chart of the **percentages reason for rejection** (relative to the total rejection), with the lowest 10 percent depicted more detailed in a second (smaller) pie chart for Supplier 1;
16. Pie chart of the **total quantity delivered without rejection and total rejection** (percentage relative to the total quantity delivered) for Supplier 2;
17. Pie chart of the **percentages reason for rejection** (relative to the total rejection), with the lowest 10 percent depicted more detailed in a second (smaller) pie chart for Supplier 2;

E.7 Sheet 9: "Validation"

An overview of the last sheet of the tool, called "Validation" can be seen in Figure E-11. The function of this sheet is to fill the drop-down menus with the correct components. In case other components need to be added, the user can simply add the components in this sheet. No user interaction is necessary on this sheet.

E.8 Screenshots

E.8.1 Sheet “Retour”

#	Documentnummer	Klant-/leverancierscode	Klant-/leveranciersnaam	Boekingsdatum	Vervaldatum	Artikelnummer	Artikel-/serviceomschrijving	Hoeveelh	Regeltotaal	Inkoop tekst	Opmerkingen
[redacted]											

Figure E-1: Overview of the fist sheet of the quality issues tool, called "Retour". Data censored due to confidentiality.

E.8.2 Sheet “Supplier 1” & “Supplier 2”

#	leverancier	Artikelnummer	Artikel-/serviceomschrijving	Documentnummer	Ontvangen	Boekingsdatum
[redacted]						

Figure E-2: Overview of the second sheet of the quality issues tool, called “Supplier 1”. Data censored due to confidentiality.

#	leverancier	Artikelnummer	Artikel-/serviceomschrijving	Documentnummer	Ontvangen	Boekingsdatum
[redacted]						

Figure E-3: Overview of the third sheet of the quality issues tool, called “Supplier 2”. Data censored due to confidentiality.

E.8.3 Sheet "Retour5"

#	Documentnummer	Klant-/leverancierscode	Klant-/leveranciersnaam	Boekingsdatum	Vervaldatum	Artikelnummer	Artikel-/serviceomschrijving	Hoeveelheid	Regeltotaal	Inkoop tekst	Comment

[redacted]

Figure E-4: Overview of the fourth sheet of the quality issues tool, called "Retour5". Data censored due to confidentiality.

E.8.4 Sheets “Supplier 15” & “Supplier 25”

#	leverancier	Artikelnummer	Artikel-/serviceomschrijving	Documentnummer	Ontvangen	Boekingsdatum
[redacted]						

Figure E-5: Overview of the fifth sheet of the quality issues tool, called "Supplier15". Data censored due to confidentiality.

#	leverancier	Artikelnummer	Artikel-/serviceomschrijving	Documentnummer	Ontvangen	Boekingsdatum
[redacted]						

Figure E-6: Overview of the sixth sheet of the quality issues tool, called "Supplier25". Data censored due to confidentiality.

E.8.5 Sheet "Artikel"

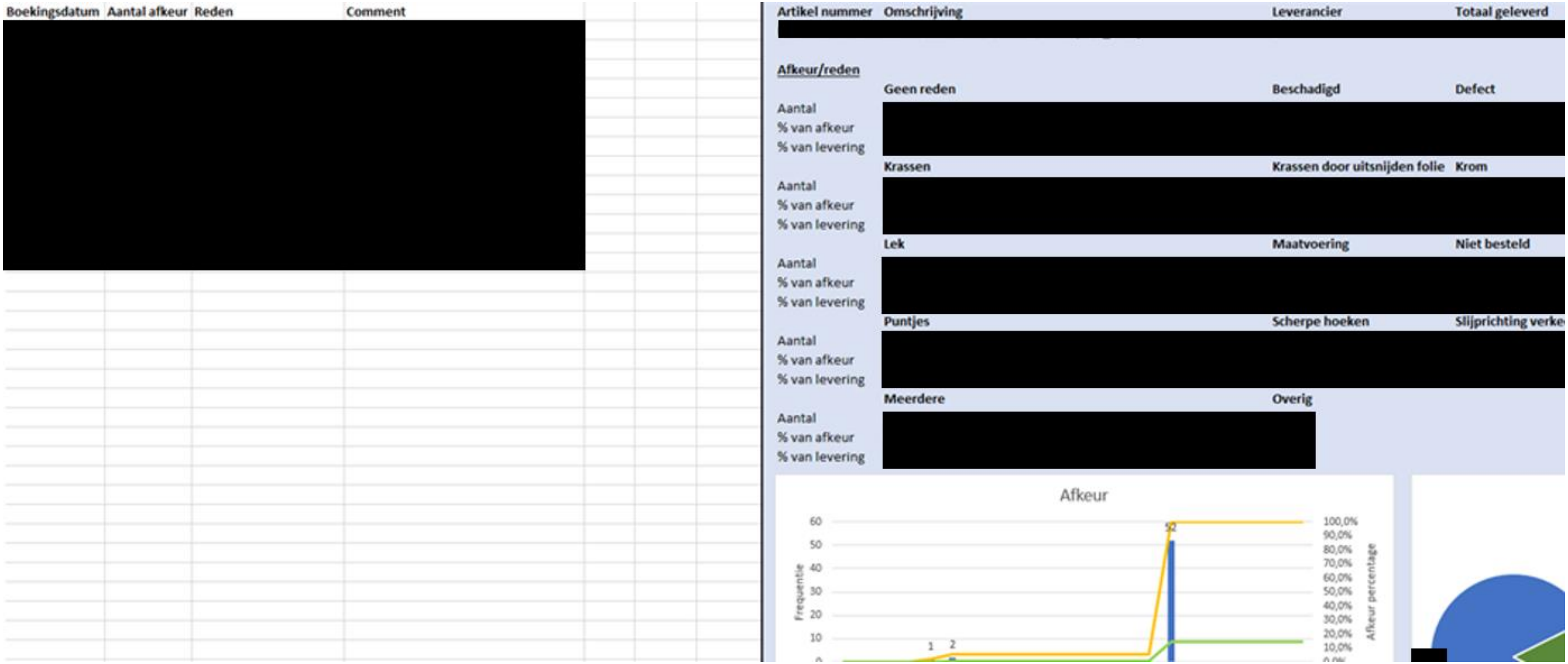


Figure E-7: Overview of the seventh sheet of the quality issues tool, called "Artikel". Data censored due to confidentiality.

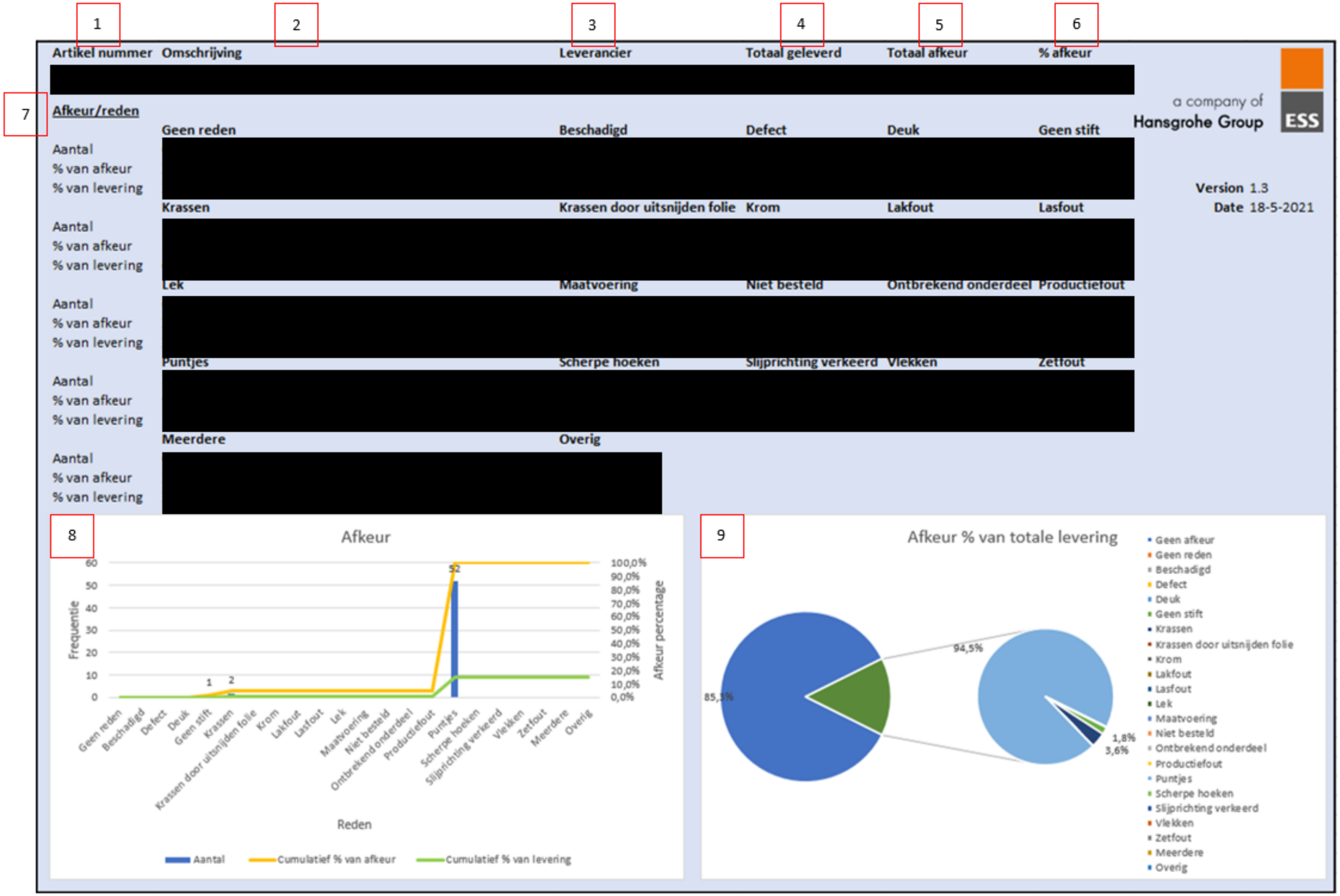


Figure E-8: Dashboard of the sheet "Artikel" more detailed (numbers correspond with enumeration in section D.4). Data censored due to confidentiality.

E.8.6 Sheet “Artikelen”

#	Artikelnumm	Artikel-/serviceomschrijv	Klant-/leveranciers	Totaal gele	Totaal afk	% afke	Geen red	Beschad	Defect	Deuk	Geen sti	Krassen	Krassen door uitsnijd	Krom	Lakfout	Lasfout	Lek	Maatvoer	Niet best	Ontbrekend onder	Productief	Puntjes	Scherpe hoe	Slijprichting verk	Vlekken	Zetfout	Meerder	Overig	Comment
[redacted]																													

Figure E-9: Overview of the eighth sheet of the quality issues tool, called "Artikelen". Data censored due to confidentiality.

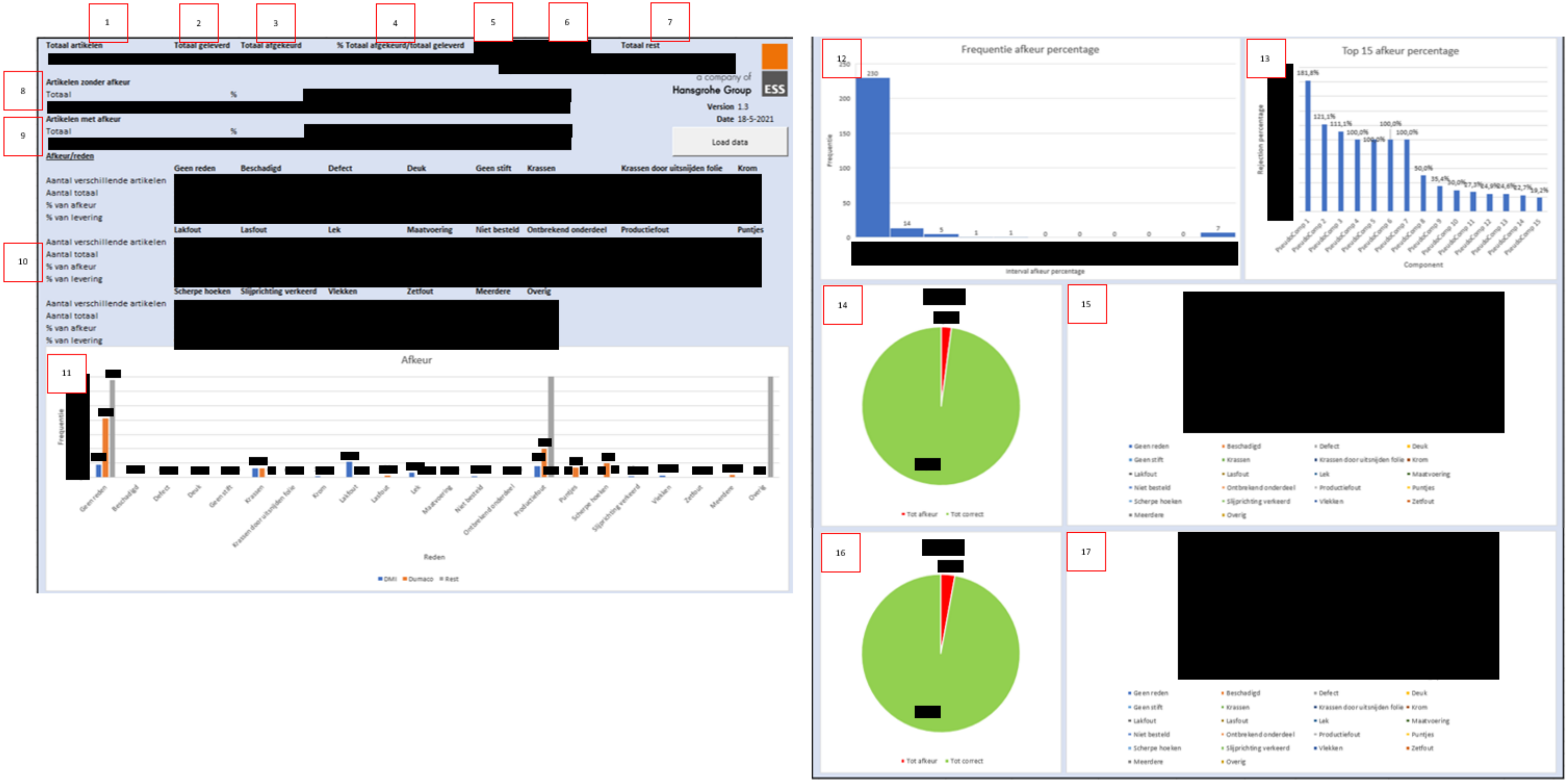


Figure E-10: Dashboard of the sheet "Artikelen" more detailed (numbers correspond with enumeration in section D.5). Data censored due to confidentiality.

E.8.7 Sheet "Validation"

Retour redenen				Leverancier	Artikelnr	Omschrijving
Geen reden	[redacted]					
Beschadigd						
Defect						
Deuk						
Geen stift						
Krassen						
Krassen door uitsnijden folie						
Krom						
Lakfout						
Lasfout						
Lek						
Maatvoering						
Niet besteld						
Ontbrekend onderdeel						
Productiefout						
Puntjes						
Scherpe hoeken						
Slijprichting verkeerd						
Vlekken						
Zetfout						
Meerdere						
Overig						
Som						

Figure E-11: Overview of the ninth sheet of the quality issues tool, called "Validation". Data censored due to confidentiality.

F. Encounter fewer quality issues at line

The last appendix contains extra information used in the process to reduce the number of quality issues discovered at the line. Section F.1 provides a description of the twelve identified solutions. Section F.2 provides extra information about the planning constructed for the implementation plan. Lastly, the most important assumptions made during the cost-benefit analysis and analysis of the potential increase in production capacity are provided in Section F.3.

F.1 Identified solutions

To discover fewer quality issues at the assembly line, solutions have been identified using a brainstorm session. Combined with solutions from literature and own experiences in the process, the following twelve ideas have been identified:

1. **Change of mindset**. By changing the mindset to a situation in which quality is seen as a shared responsibility to all departments, many rejections can be prevented. For example, there is too often no time and too much pressure to book in the components. In these cases, the quality control is postponed to the lines. By taking enough time at the goods receipt to check the quality, many problems can be prevented and costs can be saved.
2. **Sticker pallets with rejections**. If the first three products of a pallet have a quality issue, attach a sticker on this pallet and check it more elaborate later.
3. **Tools for checking quality**. Tools that ease and make the checking of quality issues more objective can help the goods receipt process to filter out more quality issues.
4. **Capture and standardize quality assessment procedure goods receipt**. The current goods receipt process is not standardized and, therefore, parts of the process can be omitted easily. By capturing the quality assessment procedure, it is clear for suppliers what and how will be checked. This way, a supplier can adjust its own quality control.
5. **Retrain workers goods receipt**. By giving a training on quality issues for the workers at the goods receipt, the workers can filter out the quality issues better and faster. This way, less components with quality issues are coming in the process and are discovered at the line.
6. **Hire extra quality employee**. An employee that is specialized in quality (issues) can faster and better check the components on quality. Besides, the other workers at the goods receipt are able to spend their time on the rest of the goods receipt process and the capacity increases.
7. **Move responsibility more to suppliers**. By making better arrangements with the suppliers, the responsibility of quality control can be moved to the suppliers. Consequently, less quality issues will be delivered and, therefore, in the process. Before this solution can be implemented, however, many actions are required first (standardized requirements, setting of Key Performance Indicators (KPIs), etc.).
8. **More frequent contact with suppliers**. By contacting suppliers and substantiating contact with data, suppliers get a better insight in the problems and quality issues that play. This way, adequate actions can be identified to counteract the problems and quality issues.
9. **Spread delivery of components**. On Wednesdays and Fridays, more components are delivered compared with the other days. Because a lot of components need to be checked and booked in the system at once, the quality control is done quickly. By spreading and equalizing the delivery of components over all days of a week, the pressure to perform a quick quality check can be decreased.
10. **Reconsider suppliers**. When a component is delivered structurally with quality rejections and the supplier is not able to solve these, it can be good to think about searching a new supplier.
11. **Redesign components**. Some components are designed too complex. Therefore, it is hard for suppliers to produce and deliver these with good quality.
12. **Capture requirements of components / products**. When all requirements are fixed (e.g., color, dimensions, etc.), it is clear which requirements a certain component must have.

F.2 Planning implementation plan

The first solution, capture and standardize goods receipt process, is a joint responsibility of the goods receipt itself (which has to use the new process) and the quality manager which has to guide the implementation and make changes when needed. It is expected that it will take about two months to fully develop and implement the solution. The rest of the year (light red in Table F-1) is for improving the process and stepwise implementing the requirements and allowable deviations within the process.

The second solution, capture the requirements and allowable deviations, does also start from the beginning and is also a joint venture, this time between the quality department and the R&D department. Together, the requirements, allowable deviations and how to measure these must be captured. This solution is a time-consuming process and, therefore, is spread over the complete first year. When the requirements and allowable deviations of some components have been captured, these can be implemented stepwise for each component in the goods receipt process.

The solution of the quality tools also starts from the beginning but only takes a month here. This month is meant to brainstorm and explore the different quality tools that can be implemented so these can be considered during defining of the requirements and allowable deviations (and no rework has to be done). This exploration is a joint venture of the R&D, quality department, goods receipt. More specific actions and tools will be identified and implemented during the second half of the year, when the majority of the requirements have already been established. Then also the purchase department gets involved, as these are responsible for buying the tools.

The fourth and fifth solution, move responsibility and more frequent contact, are the next two solutions. No collaboration between departments are needed as the purchase department is the only party responsible for the suppliers. The fourth and fifth solutions start respectively in the beginning of the second year and in the end of the first year. The reason the first one starts later is that the suppliers must be given some time to adapt to the requirements before the responsibility can be moved fully. The more frequent contact can already be initiated as soon as the requirements are clear. Both solutions can be started for only parts of the suppliers earlier, when the requirements for these products are already clear. This “soft” start is depicted in the planning with a lighter color.

The last solution, reconsidering of the suppliers, can only be started on the very long-term. Reason for this is that first suppliers must be given time to adapt to the requirements and to change its behavior when confronted. The department responsible for this solution is the purchase department. Before suppliers can be judged on performance, a dashboard containing different KPIs must be built. As this takes time to build properly, this can be initiated starting the first year. The information of the dashboard can also be used during the contact with suppliers. When finished, performance can be judged fully from the half of the second year onwards. This performance must be monitored constantly and after some time, suppliers can be reconsidered (at least from year three onwards).

F.3 Assumptions effect solutions

During the cost-benefit analysis and analysis of potential increase in production capacity, some assumptions regarding the costs, benefits and other numbers had to be made. This section summarizes the most important ones.

The following assumptions are the most important assumptions made during the analysis of the costs of the solutions:

- Average salary non-production employee: €30.00. Consisting of:
    - Average hourly salary 2020 (CBS, 2020): €24.08.
    - Factor incorporating extra costs (power, additional tools, coffee, etc.).
- A year has 45 working weeks, taking into account holidays and days off.
- Total costs new tools: €1,800.00.
    - Only in case a relatively inexpensive set of tooling is chosen, with keeping the existing computers and other tools.
    - When this all must be replaced, costs will probably rise to about €3,000.00 - €5,000.00 (according to one of the R&D employees).
- The costs of not being able to deliver an item to a customer is omitted.
    - Reason for this is that in an interview with both the export manager of Germany and France, it is pointed out that customers are willing to wait longer because these products are luxury products.
    - Moreover, the products do not form the basis of the bathroom and can, therefore, also be built-in later. In case a customer cannot wait longer, an alternative is proposed and mostly accepted.
    - Thus, there are no real cost in not delivering an item in time and, therefore, these are omitted here. In reality, however, there would be this kind of costs.

As for the costs, also some conclusions had to be made to quantify the benefits of the solutions. The most important assumptions made here are:

- Average salary non-production employee: €30.00. Consisting of:
    - Average hourly salary 2020 (CBS, 2020): €24.08.
    - Factor incorporating extra costs (power, additional tools, coffee, etc.).
- Average salary production employee: €15.00 (including extra factor, based on findings from interviews).
- Activities of the quality manager: €50.00.
    - Based on the costs Hansgrohe charges (interview finding).
    - The quality manger does not do all the processes for all issues separately but only is involved when there is a large number of issues. This would make the cost of a quality issue more expensive. As not all quality issues take the same amount of time, however, it is assumed that this is compensated by charging the €50.00 for each issue.
- The number of orders in year one is the same as 2020.
- Year two and three: respectively an increase of five precent point relative to year one and two.
- The percentage of orders with a quality issue stays constant the next three years when no actions are taken (22%).
- On average 2.2 quality issues were discovered per order with a quality issue.
    - This number stays constant during year one to three.
- The expected decrease in orders with a quality issue differ per year.
    - Based on an own consideration of the solutions (and again verified with the quality manager).
    - There is a difference between the years as some solutions are only implemented after a year (see planning) and it is expected that the full effect of some solutions will only be seen after some time as solutions reinforce each other.
    - Year one: 20.0%.
    - Year two: 18.5%.
    - Year three: 17.0%.

To calculate the potential increase in production capacity, more assumptions were necessary. The most important assumptions used during the calculations are:

- Production days 2020: [redacted].
    - Slightly higher than the forty-five working weeks with five days assumed in the cost calculation because some weeks production also takes place on Saturdays.
- There are eight working hours per day.
- The average number of workers per order is [redacted] (based on 2020).
- The total number of products produced on the line is [redacted] (in 2020, including semi-finished products).
- Decrease in orders per year with a quality issue when implementing the solutions are the same as assumed for the benefits (see above).
- Average number of quality issues per order is 2.2 and stays constant the next three years.
- Per issue, three minutes are wasted (see Table 21).
    - Probably more time is wasted due to finishing and switching to a new order and not being useful (talking, working with a low pace, etc.). However, it is difficult to give an expected duration to these activities and are, therefore, omitted in the estimated duration of three minutes.