Bachelor thesis

Reducing expectation and variability of manufacturing lead time by improving product quality

A case study at the company Teplast

Jan Groeneveld – s1112856
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MANAGEMENT SUMMARY

Teplast's management requested a research on how the customer lead time (LT) can be optimized in order to ensure a higher order delivery reliability and to reduce the current LT of four weeks to create a competitive advantage.

Because of the limited period of time we focus the research only on the manufacturing lead time (MLT). This includes the time, when a production orders arrives at the first production station until it is delivered to the customer. We find that rework, which is caused by product failures, increases the variability and expectation of the MLT, because rework is a detractor that increases the variability of the effective process time and leads to more and unnecessary setups. Furthermore, product failures waste capacity, time and material and are therefore really costly. In case that products with poor product quality are delivered to the customer, they can also cause a bad reputation leading to losing customers. Therefore, we determine product failures as Teplast's core problem. This research analyses this core problem in three parts: the error analysis, the quantification of problem and the impact of the problem.

Analyzing the causes of the errors we find the following problems:

- Sloppiness during checking of the product
- Lack of preparation
- Material failure due to short storing times
- Lack of communication

We also find that 79% of errors occur at the machines and especially at the three machines of type M1, which belong to the suction plates. This number is not surprising, because 44% of all production orders pass one of these M1 machines and therefore it is logical that the most products fail at these machines. In addition, new machine operators normally start at these machines.

Poor product quality can be quantified by the amount of failed products. Failed products are products that are defective and need to be reworked or scrapped, which means they have to be remanufactured, what is worse. A production order is categorized as defective (or scrapped), if at least one of the products is defective (or scrapped). It is also important to note, where product failures are detected. Product failures that are detected by the customer (external reclamation) are always worse than product failures that are detected b the quality check (internal reclamation). Consequently the product quality can be quantified by the amount of defective or scrapped production orders, which return as either internal or external reclamations.

Quantifying the product failures at these M1 machines, gives the failure rates:

- 9.7% M1 production orders return to production due to poor product quality
    - p_{S_E}= 0.8% (scrapped M1 production order returning from the customer)
    - p_{S_I}= 1.8% (scrapped M1 production order returning from the quality check)
    - p_{D_E}= 0.8% (defective M1 production order returning from the customer)
    - p_{D_I}= 6.3% (defective M1 production order returning from the quality check)
- 90.3% M1 production orders are delivered to the customer with a good product quality

We used this failure rate in the calculation of the MLT. We can only compute an approximation, but the results of the impact analysis show that

- if the product failure rates ($p_{S_E}, p_{S_I}, p_{D_E}, p_{D_I}$) would be decreased by 20%, the MLT would be reduced by 7%.

In order to reach these 20% or better, Teplast needs to change the current situation to improve the production quality. Therefore we have established some alternatives concerning the Teplast's core problem.

On a short term Teplast can use the following alternatives:

- An integrated quality check at the machine: This can be done with checklists, where the operator writes down his measurements. Therefore he notices errors directly and can immediately take action to fix them.
- Quality check of all technical drawings: Right now only the technical drawings for the suctions plates are checked. This could be also done for machines.
- Remarks for the finishing department: At the finishing department the workers often have to do the same working procedures, which can lead to errors, if something is not the same. Remarks of the work preparation department could help to provide that.
- More material in stock: If the material is stored longer, the workers can process the material more easily, which leads to less material failures.

On a long term Teplast can use the following alternative:

- Reducing the WIP level: Teplast needs to accept less production orders, if the production is running out of capacity. Lower WIP levels lead to better quality and according to Little's Law the same amount of production orders can be done in the long run, because a lower WIP level leads to a shorter lead time.

There are also other recommendation, which do not concern the core problem, but nevertheless they can be helpful for Teplast:

- More measurements: Teplast does not measure realized process times, rework and scrap rates, external and internal reclamations and machine failures. This data is important to establish the improvement of the company.
- New machine M1: While computing the MLT we noticed that the utilization of M1 is really high. The utilization will decrease, if the product failure rate decreases. Teplast could also consider buying a new machine type M1.
- No overlapping of shifts: Every day the afternoon and night shift overlap. Most of the times this is a waste of human capacity.

DEFINITIONS AND NOTATIONS

In the following the important terms of the research are explained for a better understanding of the research. These are definitions used by Teplast, the book “Factory Physics” (Hopp & Spearman, 2000) and a lecture presentation (Al Hanbali, 2015).

Coefficient of Variation (CV): the relative measure of the variability of a random variable. In many cases, it turns out to be more convenient to use the squared coefficient of variation (SCV).

Customer lead time (LT): the length of time between the instant when an order is placed and the instant at which the order arrives.

Cycle time (CT): total time between a release of a production unit into station/system until it exists, i.e., <u>including</u> possible waiting. It is a random variable.

Checking time: time products are being measured and checked for errors at the station.

Effective process time (t_e): the time from when a job reaches the head of the queue until it is ready to depart the station. So, it includes not only the raw process time, but also any detractors (machine down time, setup time, operator induced outages, etc.).

External reclamation: product failures which are rejected by the customer (sometimes there are also rejections even though the product is good).

Failed products: product is not satisfactory for the customers (product quality is not good). The term failed products is used interchangeably with the terms product failure and poor product quality.

Internal reclamation: product failures which are rejected by the quality control.

Line cycle time (LCT): the average cycle time in a line is equal to the sum of the cycle times at the individual stations less any time that overlaps two or more stations.

Machine type 1 (M1): there are three machines of type 1: Machine 1A, 1B and 1C.

Machine 1 production order (M1 production order): production orders allotted to machine 1A, 1B or 1C (§5.1).

Manufacturing lead time (MLT): is the time allowed on a particular routing.

Move time: time jobs spend being moved from the previous workstation.

Order line: is a production orders belonging to a customer.

Piece number: the size of a batch, number of products in a batch.

Poor product quality: product is not satisfactory for the customers (product quality is not good). The term poor product quality is used interchangeably with the terms failed products and product failure.

Processing time: time a job is actually being worked on (e.g. by a machine).

Product failure: product is not satisfactory for the customers (product quality is not good). The term product failure is used interchangeably with the terms failed products and poor product quality.

Production order: one job going through the manufacturing processes.

The terms production order, job or batch (only when the batch size of the job is bigger than one) are used interchangeably.

Product quality: in this research three different levels of product quality are categorized:

Good: Product can be sent to customer

Defective: Products needs to be reworked

Scrapped: The product is has grave errors and needs to be done all over again

Queue time: time jobs spend waiting for processing at the station or to be moved to the next station.

Raw process time t_0: time required to process a part in a machine, i.e., excluding possible extra waiting.

Remanufacture: a product failure categorized as scrap and therefore cannot be used anymore and need to be produced again.

Rework: when a product is defective it needs to be processed at the machine again.

Routing: sequence of workstations passed through by a part.

Setup time: time a job spends waiting for the station to be set up.

Station Capacity: the capacity of a single station is defined as the long-tern rate of production if materials were always available. Note that we must account for failures, setups, and other detractions when computing capacity.

Throughput (TH): production output of machine/station/system per unit of time.

Utilization: the utilization of a station is defined as the ratio of the rate into the station and the station capacity.

Variance: a measure of variability (spread) of a random variable.

Variability of process times (PV): measured in terms of the coefficient of variability of the effective process times C_S.

Wait-to-batch time: time jobs spend waiting to form a batch for either (parallel) processing or moving.

Wait-in-batch time: amount of parts present in workstation or system.

Work-in-process (WIP): amount of parts presents in workstation or system.

Terms such as normal and average; realized and effective; production and manufacturing are used interchangeably.

TABLE OF CONTENTS

1 CONTEXT

This project is conducted for the bachelor graduation of Industrial Engineering and Management. It has a limited time of three months. The research is made at the company Teplast in Ahaus at the production operations department.

1.1 THE ORGANIZATION

The company Teplast was founded in Ahaus (Germany) in 1994 and is specialized in the production of plastics. The company owns a CNC machine park of 13.000 m² and employs around 80 workers excluding part time workers. Teplast is known for being a problem solver. Good technical equipment and highly qualified workers enable good quality and solve complex tasks within the plastics production. Quality and customer satisfaction are the key points of the corporate philosophy.

Figure 1: Teplast's Building complex.

Teplast does not produce an own product but instead manufactures products designed by customers. As a result, Teplast is fully customer-oriented and follows a pull production system. Other companies (business-to-business) make production requests by sending a detailed drawing (CAD file) of the desired product. One customer can make multiple product requests. Every separate product order belonging to one customer is called an order line which is equal to a production order. If multiple different products are ordered, every different product is an order line. In addition, every order line has a piece number which indicates how many products or pieces of this order line have to be produced. An order line with more than one pieces can also be called a batch. The amount of pieces can vary from 1 up to 500, but in general, the piece number is between 1 and 50. Teplast produces different types of orders:

1. *Capacity orders*
   The customer buys machines hours. If Teplast cannot provide these hours as agreed, there will be a penalty.
2. *Blanket orders*
   The customer asks for a certain amount of a product in a certain period of time. The products are to be delivered bit by bit, whenever the customer asks for it.
3. *Normal orders*
   Normal orders are one time orders. After price calculation the customer will get an offer and can make the purchase.

The production is divided into three shifts: morning (5.00 - 14.30), afternoon (14.30 - 20.00) and night (20.30 - 5.00). Teplast has a lot of normal orders with a piece number of only 1. These single production orders are mostly processed during the day, because they need more support. During the night production series are produced. Teplast produces plastics for several branches of applications:

- Mechanical engineering
- Food industry
- Laboratory, medical, analytical technology
- Clean-room technology
- Transport / handling technology
- Vehicle / automotive industry
- Packaging industry
- Print / textile industry
- Agricultural and construction sectors
- Electrical industry
- Construction of apparatus
- Store construction
- Consumer goods
- Acrylic processing
- Cookware for households and caterings

Examples of the products are shown in Appendix A.

1.2 THE OBJECTIVE OF THE RESEARCH

Since customer orientation is very important to the company, Teplast always wants to deliver on time and ensure good product quality. For the orders categorized as normal or blanket orders, the company has the objective to deliver within four weeks (independent from the quantity of the order). These four weeks are defined by Hopp and Spearman (2000) as customer lead time (LT) as it is “the amount of time allowed to fill a customer order from start to finish” (p. 321). However, at the moment Teplast is not always able to achieve delivery within these four weeks, because there is a high level of variability within the LT.

Teplast’s management requests a research on how the LT can be optimized in order to ensure a higher order delivery reliability and to reduce the current LT of four weeks to create a competitive advantage. While optimizing the LT the product quality most not be affected in a negative way.

1.3 THE METHOD

For this research the method called “Algemene Bedrijfskunde Probleemaanpak” (or “The Managerial Problem Solving Method”) from Heerkens and Van Winden (2012) will be used to solve the problem(s) which will be discussed in the following chapter. This method consists of the following steps:

1. Problem identification
2. Problem approach
3. Problem analysis
4. Generation of alternatives
5. The decision/ The recommendation
6. The implementation
7. The evaluation

Given the time limit of three months, only the first five steps of the method will be taken into account.

2 THE PROBLEM IDENTIFICATION

As discussed in §1.2, the objective of this research is to optimize the current LT of Teplast, in order to ensure higher order delivery reliability and to shorten the current LT. We need to reduce the variability and the expectation of the LT, to achieve this objective. This chapter will first give an overview of the logistic processes within Teplast to show which processes within the company determine the LT and on which part of the LT this research will focus. Thereafter, the most relevant problems which have an influence on this part of the LT are identified. We will first describe the theory behind the problems and with use of interviews and observations we will describe Teplast's situation thereafter. At the end a cause and effect diagram and the scope will give a clear overview of the focus of this research.

2.1 OVERVIEW OF THE PROCESS

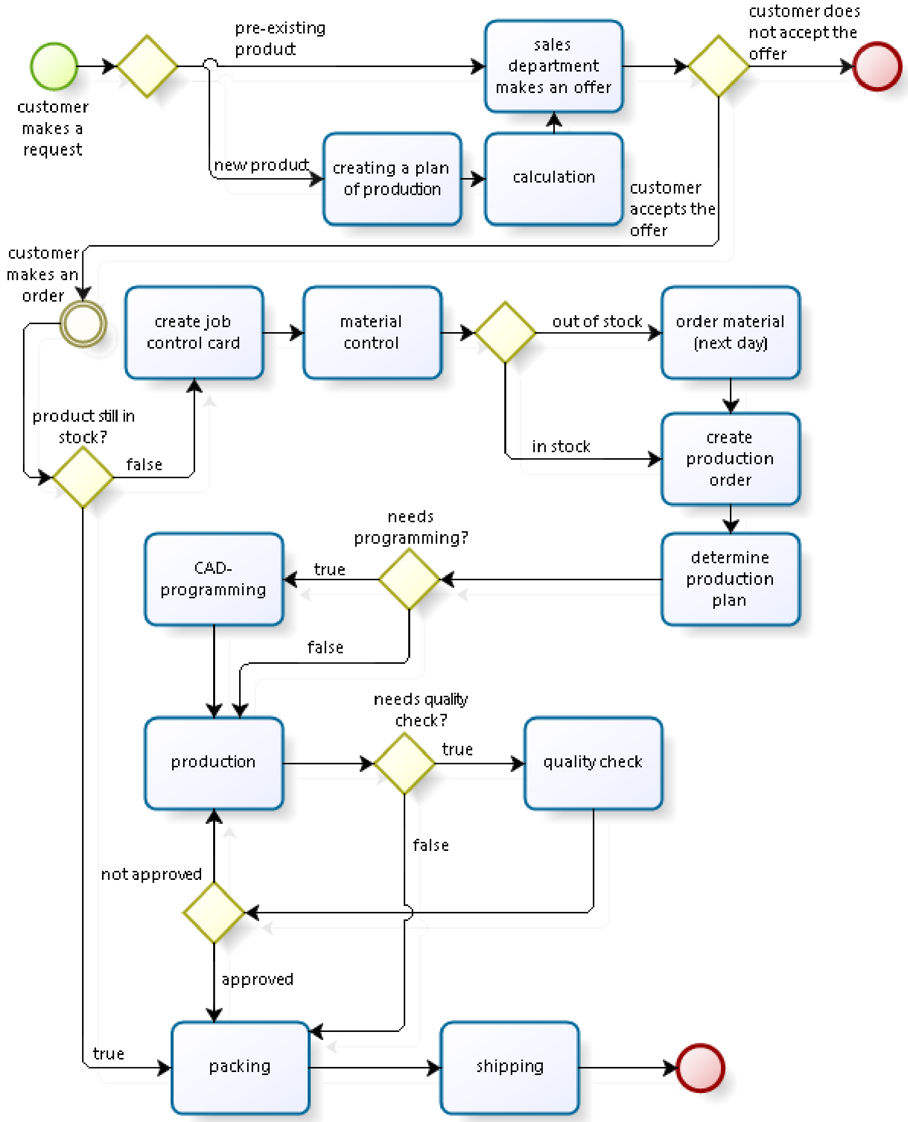


Figure 2: An overview of the whole logistic process at Teplast.

As shown in Figure 2 the process begins if the customer makes a request. The request includes sending a CAD file and saying which material is needed. In case it is a new product the work preparation department will create a plan of production and calculates a price and estimates the LT.

Afterwards the sales department makes an offer with the estimated time and price, which the customer either accepts or rejects. When the order is accepted it will be checked whether there are still finished products in stock. In case there is nothing in stock, a job control card is created and depending on the availability of material in stock, material will be ordered the next day. Thereafter the order is going to the work preparation department where the production order is made. The production plan will be determined and in case the order needs programming the order is going to the CAD office. Then the actual production starts. The material is sawed and brought to the machines. After manufacturing the products need some finishing. In most cases a quality check is done, because either the customer has requested for it himself or it is an important customer for Teplast. According to the heads of the production and sales department around 80% of the production orders are checked before finally packing and shipping the order. For big batches random samples are used for the quality check.

Applying Hopp and Spearman's (2000) definition of LT to Figure 2, we can say that the LT of Teplast includes the time from the moment the customer makes an order until the shipping of the product. However, the processes before this point, including the creation of the production plan and the calculation, are not entirely unimportant, because errors made during these steps complicate the production planning, hence affect the LT. Nevertheless, due to the limited period of three months, the focus of this research will lay on the manufacturing part of the LT, hence the manufacturing lead time (MLT). The MLT as such is defined by Hopp and Spearman (2000) as "the time allowed on a partifuclar routing" (p.321). A routing is identified as "a sequence of workstations passed through by a production order" (Hopp & Spearman, 2000, p.216). In the context of Teplast, the sequence of working stations and therefore the MLT, starts with the production and ends with the shipping to the customer as shown in Figure 2.

2.2 IDENTIFYING THE PROBLEM

In this part we identify the problems concerning the MLT of Teplast by using the theory of the book "Factory Physics" from Hopp and Spearman (2000), the results of conducted interviews and the observations of the total production line. As MLT is a part of the LT, the LT decreases with the MLT. Now we need to know what affects the MLT, in order to reduce it. Hopp and Spearman (2000) characterize MLT as: "The manufacturing lead time for a routing that yields a given service level is an increasing function of both the mean and standard deviation of the cycle time and the routing." (p. 323). In this regard we speak of the station's cycle time (CT), which is the total time between a release of a production order into station and its existence, i.e. <u>including</u> possible waiting (Al Hanbali, 2015). Considering the characterization of the MLT, we can conclude that the following two points cause a long and variable MLT.

1) <u>Long effective cycle time at a station</u>
2) <u>High variability of station's effective cycle time</u>

We add the term effective here, because we want to analyze the realized times and not the expected times.

2.2.1 Long effective cycle time at a station

Let us first take a closer look of what causes a long cycle time a station. Hopp and Spearman (2000) mention the components of the CT, which gives a good understanding of what the CT contains. However, the original formula as defined by Hopp and Spearman (2000, p. 315) does not apply entirely to Teplast. Therefore we developed a changed version of the formula:

Cycle time = move time + *queue time* + setup time + processing time + checking time + *wait-to-batch time* + *wait-in-batch time*

Definitions from the components of cycle time are derived from Hopp and Spearman (2000, p. 315)

Move time: “time jobs spend being moved from the previous workstation”.

Queue time: “time jobs spend waiting for processing at the station or to be moved to the next station.”

Setup time: “time a job spends waiting for the station to be set up.”

The setup time at the machine is more complex than at the other stations. The workers need to tune the machine and to program and run the CNC program, so it includes: preparation time (reading and understand the drawing), programming time and tooling time.

Processing time: “time a job is actually being worked on (e.g. by a machine)”

Wait-to-batch time: “time jobs spend waiting to form a batch for either (parallel) processing or moving.”

Wait-in-batch time: “amount of parts present in workstation or system.”

Checking time: time products are being measured and checked for errors at the stati on.

Basically, the CT formula consists of delay times (queue time, wait-to-batch time and wait-in-batch time) and process times (move time, setup time, processing time and checking time).

Regarding the process times, taking a station’s process times together determines the time, which is required to process a part at a station, i.e., excluding possible extra waiting (Hopp & Spearman, 2000). We differentiate between two process times, which are the raw (or expected) process time t_0 and the effective process time t_e. The difference between these two process times is caused by excluding or including detractors, such as extra setups, downtime, rework and machine failures (Hopp & Spearman, 2000). The raw process time is the natural process time at a station (without detractors) and the effective process time is the mean effective process time (average time required to do one job) including all detractors.

Regarding the process times the processing time depends on machines and the technology used therein, so it does not have a lot of potential of being optimized and is therefore out of scope. Reducing move times requires restructuring the whole production hall to create more efficient moving ways, which will not be a part of this research. The reduction of checking time is highly depending on human factors and will therefore not be analyzed. Setup time can be reduced in two ways, by reducing the setup time itself and by reducing the amounts of extra setups. The amount of extra setups is a detractor leading to a longer effective process time. At Teplast we find a lot of extra setups caused by rework, remanufacturing or insufficient planning. The setup time itself depends on the operator and the preparation he gets. Preparation time is important, but not necessarily at the station. High preparation times at the machine lead to lower runtimes of the machine. The programming and tooling time is hard to optimize, since it depends on the operator.

Regarding the delay times, Schutten (2014) indicates that from all the CT’s components, the delay times require the most of the CT. Regarding the delay times within Teplast, the wait-to-batch time and wait-in-batch time will not be analyzed, because the setup times are high and batches normally not that big, and therefore it can be assumed that in most of the cases it is better to not divide batches. Long queueing times are caused by high variability of effective process times and high utilization (Hopp & Spearman, 2000, p.325). Due to many detractors in Teplast's production, the company encounters a high level of variability of effective process times and a high utilization is caused by insufficient production planning and rework (see §2.23). These two together lead to high queueing times.

2.2.2 High variability of station's cycle time

The variability of station's cycle time increases with the level of variability of effective process times (PV). Hopp and Spearman (2000) state: "Increasing variability always degrades the performance of a production system." (p. 295) and in addition that more variability increases congestion and cycle time and therefore increases the MLT. According to Hopp and Spearman (2000) high variability can have different causes:

- Natural
  - Machines
  - Material
  - Operators
- Detractors
  - Setups
  - Random outages
  - Operator availability
  - Recycle (Rework)

Within Teplast there are problems with scheduling orders regarding the availability of material, operators and machines, which cause variability. In addition too many setups and rework lead to a high variability within the production.

2.2.3 Impact of rework

Rework has a major impact on the MLT, since it increases both the mean and standard deviation of cycle time. "For a given throughput level, rework increases both the mean and standard deviation of the cycle time of a process." (Hopp & Spearman, 2000, p. 392). Hopp and Spearman (2000) indicate that "rework robs capacity and contributes greatly to the variability of the effective process time." (p.260). Furthermore they conclude that, utilization increases nonlinearly with rework rate

At Teplast it was observed that products, which need rework will get priority and will therefore destroy the old schedule and increase the setup time by extra (or unnecessary) setups. Failed products can make the whole process useless. In case the failure is not noticed before the quality check or the customer, there are two options: reworking or remanufacturing. Reworking means that the product has to be adjusted and remanufacturing means that the whole product is scrapped and therefore it needs to be done again (sometimes even new material has to be ordered). Either way it increases the PV and MLT.

2.3 CAUSE EFFECT DIAGRAM

In §2.2 we found that generally there are two main points leading to a longer MLT, namely long CTs and high variability of CTs, and that both are affected by rework. The following Figure 3 gives an overview of the problems leading to these points. In this diagram some points are highlighted.

- The two mains points which have a huge impact on the MLT (as mentioned above) are underlined
- The MLT itself, because optimizing the LT is the objective of the research
- The high amount of failed products, because it is determined to be the core problem (§2.4)

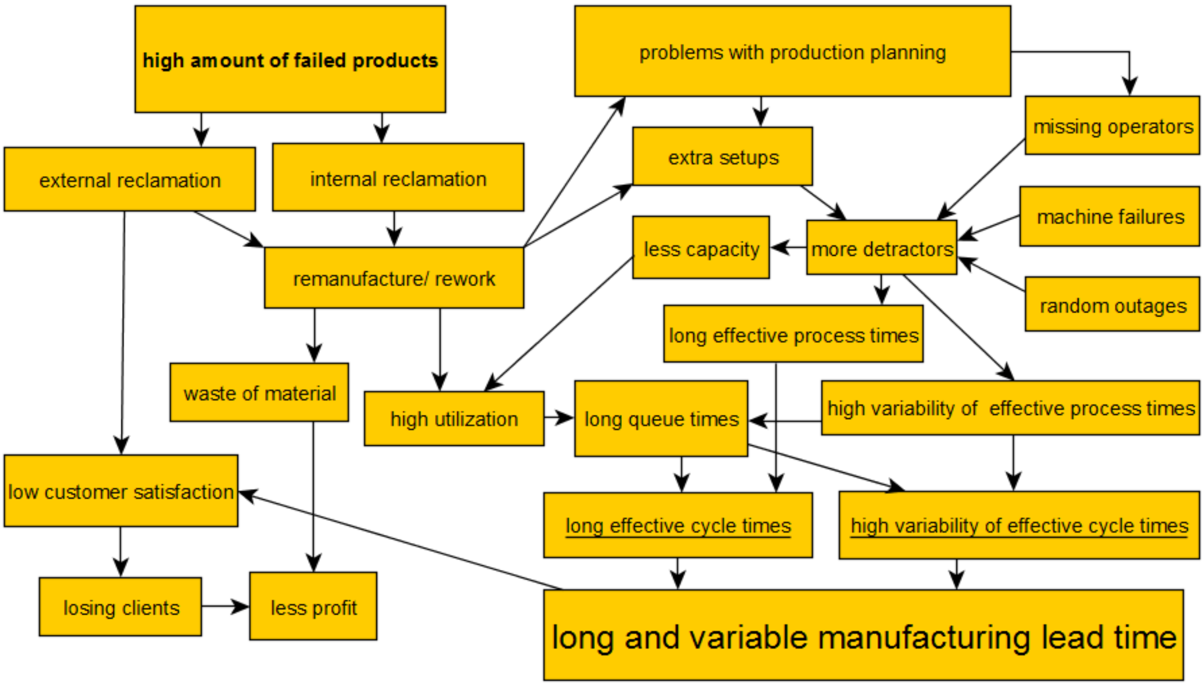


Figure 3: Cause effect diagram, showing the connections of problems, which are finally leading to a longer manufacturing lead time.

2.4 Scope

First of all, due to the limited time of three months it is not possible to analyze all factors influencing the MLT as shown in Figure 3. Detractors like random outages or machine failures will be out of scope. Even though these factors have an effect on the MLT, Teplast does not collect this kind of data and for analyzing purposes this data is needed.

Two core problems are remaining: high amount of failed products and problems with production planning. Production planning is a very broad topic and takes time to analyze. Besides, production planning is also influenced by remanufacture and rework, therefore we choose the high amount of failed product as our core problem. Now we need to define failed products (or product failures). Failed products can be broadly defined as the products, which do not meet the product quality criteria. Hopp and Spearman (2000) distinguish two types of quality, which they define as:

"Internal quality refers to conformance with quality specifications inside the plant and is closely related to the manufacturing-based definition of quality. It is typically monitored through direct product measures such as **scrap and rework rates** and indirect process measures such as pressure (in an injection molding machine) and temperature (in a plating bath)." (p. 384)

"External quality refers to how the customer vies the product and may be interpreted by using the transcendent, product-based, user-based or value-based definition, or a combination of them. It can be monitored via direct measures of customer satisfaction, such as **return rate**, and indirect indications of customer satisfaction derived from sampling, inspection, field service data, customer surveys, and so on." (p.384)

Applying these definition to Teplast's situation we can conclude that product quality can be measured by the amount of scrapped products and the rework rates. We will classify the product quality in three different levels: Good, defective, scrapped. Good products can be sent to the customer. Defective products needs to be reworked. For example the surface was not drilled properly. Scrapped products have grave irreparable errors and therefore need to be remanufactured.

For example the sizes of the products are not correct and therefore do not fit in the final product of the customer. Hereby it is not important how many defects the products have, it only matters if the level of damage leads to rework or remanufacturing. If the product is either defective or scrapped, the product quality is poor and it will be considered as a failed product.

The failed products can be detected during the production process, at the end of the production process with a quality check (internal reclamation) or by the customer (external reclamation). These failed products lead to a higher variability of the effective process time. If these product failures are seen during the production process it saves time, but in case of an internal reclamation or external reclamation it will take a lot of extra time. Sometimes even new material has to be ordered which increases the variability and expectation of the LT dramatically. Moreover, orders which do have to be reworked have priority and will therefore destroy the actual production planning, which also increases the number of setups. This leads to a vicious circle, because they lead to more setups, but more setups also lead to a higher failure rate due to programming and tooling errors. However, not only the MLT is increased, but also the costs, since new material and capacity (staff and machines) will be needed. In the case that a production order was not checked or did pass the quality check, but the customer is not satisfied with the product quality, it returns as an external reclamation leading to a bad reputation and a decrease of customer service. Teplast has collected data of the internal reclamations between the 20th of May and the 23th of August 2014, which showed that there were 353 production orders categorized as internal reclamations. Comparing this with the 3349 production orders, which were manufactured during that period, we get an internal product failure rate of 10.5%. This rate gives an indication, that there are product quality problems.

Therefore, this research will focus on reducing product failures, because it will reduce the amount of rework and extra setups. This leads to shorter effective processing time and less PV and consequently to a shorter a less variable MLT. At the same time it reduces costs and improves the products quality and the production planning. This is of big importance, as quality is one of the company's key points and quality and flexibility are essential for being successful with pull production (Laugen, Acur, Boer & Frick, 2005). Other problems and ideas will not be a part of the active research but will be taken into consideration in the recommendation.

Furthermore, the company established an express line for one client, which started in March 2015, meaning that these orders will get priority to be finished earlier. The LT of the express line is supposed to be 10 days. Since the express line has just been established, problems are not yet detected and will not be analyzed either. However, the express line has the privilege of getting priority in the production planning and can therefore be in conflict with rework which has the same privilege. This is important to consider when speaking of queueing problems.

2.5 Conclusion

In this chapter we limited the research to Teplast's MLT. If we reduce the expectation and variability of the MLT, we will also reduce the expectation and variability of the LT, which is the objective of Teplast's management. We determined the high amount of failed products to be the core problem of a long and variable MLT, because they lead to rework or remanufacturing. Therefore this problem can be quantified by measuring the scrap and rework rates. We can proof that last year there was a period with 10.5% product failures, which were detected at the quality check. This number does not include product failures, which returned from the customer or were fixed already before they arrived at the quality check. However, this 10.5% gives us an indication that there is a problem concerning the product quality at Teplast and we will explain in the following chapter how to approach it.

3 PROBLEM APPROACH

As we established in §2.4 identification our core problem is the high amount of product failures (high product failure rate). In §1.2 we determined Teplast's objective and in order to achieve it, we have to reduce the variability and expectation of manufacturing lead time. Consequently the main question of this research will be:

How can the product quality be improved to reduce rework and therefore the variability and expectation of manufacturing lead time?

For this problem a mixed method approach (quantitative/qualitative) will be used as interviews and quantitative material will be needed.

"A mixed methods approach is one in which the researcher tends to base knowledge claims on pragmatic grounds (e.g., consequence-oriented, problem-centered, and pluralistic). It employs strategies of inquiry that involve collecting data either simultaneously or sequentially to best understand research problems. The data collection also involves gathering both numeric information (e.g., on instruments) as well as text information (e.g., on interviews) so that the final database represents both quantitative and qualitative information." (Creswell, 2003).

The qualitative part (e.g. interviews) will focus on the causes of the problem, which will be analyzed in §5.1, and possible solutions, which will be discussed in §6. The quantitative research will be about quantifying the core problem by using scrap and rework rates (see §2.4), what will be measured in §5.2, and we will analyze the relationship between the core problem and the objective in §5.3. We will investigate to what extend the product quality affects the MLT.

Underneath the following steps and sub questions will be discussed. The following steps are according to the method called "Algemene Bedrijfskunde Probleemaanpak" (see §1.3).

<u>Literature research</u>
The literature research should give a theoretical basis to help us analyze the core problem and find solutions how to deal with the problem.

- How can the MLT be computed with taking product quality into account, in order to measure the actual impact of product quality on the MLT?
- How can product quality be improved?
  - How can errors be prevented?
  - How can inspection be improved?
  - How can the environment be enhanced?
  - Are there other possibilities to improve product quality?

By answering these questions we should gain enough knowledge to analyze and deal with the problem.

<u>Problem analysis</u>
The problem analysis should give us more insight of the problem. We need to find out more about the causes, the quantity and the impact of the problem.

To find the causes we can interview operators, workers and people in charge.

- What causes product failures? (qualitative)
  - What are possible reasons for product failures that can occur in the production?
  - Do the errors occur during the manufacturing process or before?
  - Where do most of the product failures occur?

We can quantify the problem by collecting data.

- How many products do fail (scrapped and defective products) and what is the percentage?
  - Internal reclamations?
  - External reclamations?
  - Not reported errors?

We need to collect data to use an approach, which we find during the literature research, in order to compute the impact of the product failure rate on the MLT.

- What impact does the product failure rate have on the current MLT? (quantitative)
  - What could be the MLT, if the failure rate improved?

<u>Generation of alternatives to improve product quality</u>

For this chapter we will use the knowledge we get from the literature research and the error analysis.

- How can Teplast reduce the product failure rate (qualitative)
  - What are the advantages and disadvantages of possible ideas?
  - Can we apply these ideas to Teplast's situation?

<u>Conclusion and recommendation</u>

- What is the advice concerning the core problem?
- What other problems were seen and how could they be solved or improved?

4 LITERATURE RESEARCH

In this chapter we will built the theoretical basis for this research by answering the following questions:

- How can the MLT be computed with taking product quality into account, in order to measure the actual impact of product quality on the MLT?
- How can product quality be improved?
  - How can errors be prevented?
  - How can inspection be improved?
  - How can the environment be enhanced?
  - Are there other possibilities to improve product quality?

4.1 COMPUTING THE MLT

In the problem analysis the MLT will be determined to show the impact of product failures on the LT. But lead times are a "managing constant used to indicate the anticipated or maximum allowable cycle time for a job" (Hopp & Spearman, 2000, p. 321), and for this reason we will quantify the MLT with the line cycle time (LCT), which is defined as: "The average cycle time in a line is equal to the sum of the cycle times at the individual stations less any time that overlaps two or more stations" (Hopp & Spearman, 2000, p.316). Therefore we need to calculate the CT at every station (including also transport), which is "total time between a release of a production unit into station until it exists, i.e., including possible waiting" (Al Hanbali, 2015). Hence, the CT at every station is sum of the waiting time (CTq_i) and the process time t_{0i} at a station (Zijm, 2003, p.12). That is why we need to understand more about queuing networks.

There are open and closed queuing networks. Closed queuing networks have a fixed number of jobs present in the network and open networks have jobs leaving and arriving to the network (Zijm, 2003, p. 113). We can easily identify Teplast's manufacturing system as an open network, since jobs are arriving and leaving the system.

"An open queuing network consists of a certain number of stations (i), denoted by M, where jobs may enter and leave the network at any given station. An important concept in queueing networks is the routing of jobs. The routing determines in which order the jobs visit which stations. The routing may be deterministic or probabilistic and may depend on the state of the network or be state-independent. The most widely encountered routing is the so-called Markovian routing, which is probabilistic and state-independent." (Zijm, 2003, p.38).

The routing is always different at Teplast. Not all production orders are the same and therefore they are processed at different stations. Hence, we can say the routing is probabilistic and that we have a Markovian routing. The routing is very important, since we will implement the rework rates in the routing. Consequently the resulting LCT will depend on the rework rates, so that we can see the effect on the LCT.

The next step is to see how Teplast's queueing system can be characterized. Normally queues are described by Kendall's notation. If we do not regard buffer locations,

"We speak of an A/B/n queue, when the interarrival, resp. service distribution is of type A, resp. B. The number of servers is indicated by c. The two most important interarrival and service time distributions are the exponential and the general distribution. The former is indicated by an M to reflect the 'Markovian', or 'Memoryless', property of the exponential distribution. The latter is simply

G. Of course, the G can be further specified. For instance, the letter D is used to denote a deterministic arrival process." (Zijm, 2003, p.10).

Zijm (2003) states that "Real-world manufacturing systems seldomly obey the exponentially assumptions" (p.43). Neither is it the case at Teplast, because we deal with variability (e.g. variable process times) and thus we need to apply G/G/c queues. For applying performance measure for a general single class manufacturing system, we need the same requirements as for a Jackson network, but instead of exponential distributions, we use general ones.

"A Jackson-network is a single-class open queueing network and with the following characteristics. Station i has at least one server c and the service times are exponentially distributed with parameter $\mu_i > 0$. The service discipline employed is first-come first-served at all stations. The jobs arrive from outside the network at station i according to a Poisson process with intensity γ_i. The jobs have a Markovian routing, characterized by an irreducible routing matrix P." (Zijm, 2003, p.38)

We already acknowledged that there is a Markovian routing, but Teplast does not always apply the first-come first-served service discipline, because the express line and production orders, which need to be reworked, are being prioritized. However, we can use this model, because as Winston (2000) states, the expected waiting time in queuing systems under different disciplines is the same (p.1126).

To compute the CT_i of and G/G/c queue, we find the formula (Zijm, 2003, p.21):

$$CT_i = \frac{\rho_i{}^{\sqrt{2(c_i+1)}-1}}{\mu_i c_i(1-\rho_i)} * \frac{C_{ai}^2 + C_{si}^2}{2} + \frac{1}{\mu_i}$$

The utilization of a station ρ_i can be calculated as $\rho_i = \frac{\lambda_i}{c_i * \mu_i}$. ρ_i has to be smaller than one, otherwise the network would not be stable (more jobs arrive than leave the station/system) (Zijm, 2003, p39). λ_i is the traffic (external and internal) at a station i. Furthermore we need to know more about the variability of the arrival and of the service times at the station for applying this formula. Variability can be quantified by the coefficient of variation (CV), which is denoted as C, or the squared coefficient of variation (SCV), which is denoted as C^2 (Hopp & Spearman, 2000, p.252). If we want to compute them, we find the formulas:

$$C = \frac{\sigma}{t},\ C^2 = \frac{\sigma^2}{t},$$

being σ the standard deviation and t the mean. The variability is considered to be low if C is smaller than 0.75, moderate between 0.75 and 1.33 and high when higher than 1.33. With this formula we can calculate the variability of jobs arriving externally ${C^2}_{a0i}$ and the variability of the effective processing times ${C^2}_{si}$. Calculating the SCV of the interarrival rates is more difficult. For this purpose Zijm (2003) gives the formulas of Whitt's approximations:

$$C_{aj}^2 = a_j + \sum_{i=1}^{M} C_{ai}^2 b_{ij}, \qquad j = 1, \dots, M,$$

where a_j and b_{ij} are constants depending on the input data:

$$a_j = 1 + w_j\left(\left(Q_{0j}^2 C_{0j}^2 - 1\right) + \sum_{i=1}^{M} Q_{ij}\left[\left(1 - P_{ij}\right) + P_{ij}\rho_i^2 x_i\right]\right),$$

$$b_{ij} = w_j P_{ij} Q_{ij}\left(1 - \rho_i^2\right)$$

and w_j, v_j, x_i are given as follow:

$$w_j = \left[1 + 4\,(1 - \rho_i)^2(v_j - 1)\right]^{-1},$$

$$v_j = \left(\sum\nolimits_{i=0}^{M} Q_{ij}^2\right)^{-1} \qquad j = 1, \dots, M,$$

$$x_i = 1 + c_i^{-0.5}\left(\max\left[C_{si}^2, 0.2\right] - 1\right) \qquad j = 1, \dots, M.$$

In these equations Q_{ij} denotes the proportion of the arrival flow of station j originating from station i, and is given by:

$$Q_{ij} = \frac{\lambda_{ij}}{\lambda_j} \qquad i = 0, \dots, M, j = 1, \dots, M$$

with $\lambda_{ij} = \lambda_i * P_{ij}$.

In order to calculate the LCT, we need the visit rate. The visit rate indicates the times a job passes a station. The visit rate V_i can be computed by dividing the internal and external traffic intensity at every station λ_i by the external arrival rate γ_E. Finally the LCT can by calculated as follow (Zijm, 2003, p.47):

LCT = $\sum_{i=1}^{M} V_i * CT_i$

4.2 IMPROVING QUALITY

Since poor quality leads to rework, Hopp and Spearman (2000) discuss some methods to prevent the effect of rework on the entire production.

Some companies have separate production lines, where they process all the reworks. The good thing is that the normal production is not influenced and extra setups are not an issue. The big negative point is that people will just give the responsibility to somebody else. Instead they should rather feel responsible, and do their own rework and learn from it. Especially when there is a lot of scrap, it is possible to increase the job size. So the amount of expected scrap plus a buffer are added to the actual job size. The problem here is that at some companies it will be “all or nothing”. In these cases inflating job size would be futile.

Their conclusion is that in the long term the best option is to strive to minimize the scrap and rework. Therefore the quality has to be improved.

Hopp and Spearman’s (2000) advice for better quality is:

- Error prevention (p. 384)
- Inspection improvement (p. 384)
- Environment enhancement (p. 384)
- Implementing principles of Just-in-time manufacturing (p.347)

4.2.1 Error prevention and inspection improvement

If less errors are made, the quality obviously improves. The key for errors prevention is “quality at the source” (Hopp & Spearman, 2000, p.384).

4.2.1.1 Implementing a checklist

Chao and Beiter (2001) state that there are four groups when speaking of quality tools, namely detection, prediction, passive and active prevention, and that using checklists is one tool of passive prevention. Mistakes can be seen directly when using a checklist. Checklist are also a tool of a poka-yoke system which was introduced by Shigeo Shingo (Shimbun, 1988). Shimbun states that there are three types of poka-yoke devices that lead to elimination of defects:

1. Source inspection – Checks for factors that course errors, not the resulting defect.
2. 100 percent inspection – Uses inexpensive poka-yoke (mistake-proofing) devices to inspect automatically for errors or defective operation conditions.
3. Immediate action – Operations are stopped instantly when a mistake is made and not resumed until it is corrected.

There is also an alternative to the 100% inspection. “In some situation where true 100 percent inspection was not feasible, the Japanese made use of the N=2 method, in which the first and last part of a production run are inspected. If both are good, then it is assumed that the machine was not out of adjustment and therefore that the intermediate parts are also good.” (Hopp & Spearman, 2000, p.162).

Shimbun (1988) states that one of the five best ways of poka-yoke are checklist to detect and avoid human errors. It is also acknowledged that the best inspector is the worker. In addition, everybody should be “correcting one’s own errors” (Hopp & Spearman, 2000, p.161). The checklist gives the worker responsibility for his own actions and makes him learn. Finally, optimizing is not a onetime thing but “continual improvement is the key of survival” (Hopp & Spearman, 2000, p. 166). If a checklist is implemented, we can use the following seven sequential steps of Chowdhury (2005):

1. Understand who the customers are.

2. Capture and analyze the voice of the customer.

3. Translate the voice of the customer into performance requirements.

4. Choose the best design concept to meet the performance requirements.

5. Translate the performance requirements into product/ service design parameters.

6. Translate the product parameters into manufacturing conditions (this step does not apply to a service).

7. Determine activities required to maintain manufacturing conditions or service process parameters.

After we have determined all needs of the customer, we can translate the performance requirements via the checklist into product design parameters (see step 5). That is why it is essential that the voice of the customer in step 2 is understood well, in order to know what the checklist has to contain.

A checklist is easy to implement and could be very helpful for Teplast.

4.2.1.2 Statistical Process Control

In a survey from Inman, Blumenfeld, Huang, Li and Li (2013) other quality control systems are mentioned such as: Quality function deployment, FMEA, Inspection planning, Design of experiments and Statistical Process Control. Statistical Process Control is also explained by Hopp and Spearman (2000). The basic idea is to detect defects in time and interfere whenever the process is out of control. There are two causes of variability:

- natural variability, which is relatively small and the sources are uncontrollable
- assignable-cause variation, which are larger sources and can be potentially be traced to their cause

In order to know whether the process is out of control or not measurement is needed. The measurement will be put into a chart with a lower and an upper control limit. For example:

LCL = $\mu - 3\sigma_{\bar{x}}$

UCL = $\mu + 3\sigma_{\bar{x}}$

If the measurements are not between these lines, they are assignable-cause variations. If one assignable-cause variation is accompanied by another assignable-cause variations or unusual run of above-average observations, it can be said that the process out of control. Therefore the cause should be traced and analyzed.

Statistical Process Control is used at many companies, but in order to apply it you need to measure a lot of data, which does not happen yet at Teplast, therefore it is probably not the best idea for now.

4.2.2 Enhancing environment

If the problem of the workers is neither knowledge nor skill, but motivation, quality-oriented worker training will not help. Alternatively we can use a different reward systems to motivate the workers. David Boddy (2011) states in his book that there are different ways to reward employees (p.342).

Type of system	**Explanation**
Time rate	Reward is related to the number of hours worked
Payment by results	Reward is related to the quantity of output
Skill-based pay	Reward is based on the knowledge and skills of the employee
Performance-related pay	Reward is based upon individual performance in relation to agreed objectives
Flexible benefits packages	Reward is based upon selection of benefits (for example, healthcare or company car) to suits individual's preferences and lifestyles

Table 1: Boddy's different types of paying employees.

At the moment Teplast is applying the time rate system, but they could use another system to give extra motivation.

4.2.3 Implementing Just-in-time principles

Hopp and Spearman (2000) also state that there is another alternative to improve quality, namely implementing principles of Just-in-time (JIT) manufacturing, which results in an overall increase in quality awareness and improved quality. However, it is possible to implement JIT principles without switching to JIT manufacturing. Just-in-time principles are about not isolating individual aspects of the production, but working together and optimizing the production environment, which also contributes to enhancing environment (see §4.2.2). This also means that the quality check should rather take place in the production and not in the end, which can be combined with implementing a checklist (see §4.2.1.1). Kanban systems using JIT are usually accompanied by the above mentioned tools for improving quality such as quality-at-the-source procedures and statistical process control. In addition it is usually accompanied by quality-oriented worker training, which also contributes to enhancing environment (see §4.2.2).

The JIT principles could also be helpful for Teplast, since they also contribute to the points, which were mentioned above.

Quality is "both a precondition for JIT and a benefit of JIT" (Hopp & Spearman, 2000, p.347). The basic idea of JIT is a low WIP level, high quality and continuous improvement. By WIP we mean the number of jobs (production orders) in the system. The higher the quality the lower the WIP can be. "Virtually all the benefits of JIT either are a direct consequence of low WIP levels (e.g., short cycle times) or are spurred by the pressure low WIP levels create (e.g., high quality levels)" (Hopp & Spearman, 2000, p.165). Hopp and Spearman also show with Little's Law "that it is possible to achieve the same throughput with long cycle time and large WIP or short cycle time and small WIP" (2000, p.248). The latter would be preferable, because it leads shorter cycle times, which is wanted by Teplast.

Lowering the WIP level could be a good possibility for Teplast, since it reduces CT and improves quality.

4.3 CONCLUSION

In this chapter we answered the literature questions (see §3.). Therefore we introduced queuing theory and how the LCT can be calculated. This will be of importance for §5.3, when we will compute the impact of product failures on the LCT. Furthermore we discussed possibilities to improve product quality, which we will use in §6, when we discuss alternatives to the current situation. In this regard we discussed procedures to prevent errors, improve inspections and enhance environment. For instance introducing poka-yoke normally leads to source inspection, 100% inspections and to the possibility that one can execute immediate actions to solve the problem. One of those tools are checklists, which could be very useful for Teplast. The most popular process control, is statistical process control, which is a bit more complex to implement. It is also important to enhance human capital, by quality-oriented worker training and motivating the working staff (e.g. by introducing different rewarding systems). Furthermore we also introduced JIT principles, which can be very helpful, because JIT builds on good quality. One of these principles is lowering the WIP level. In addition lowering the WIP, according to Little's Law, always shortens the CT and therefore the MLT, what is also the objective of the research.

5 PROBLEM ANALYSIS

In this chapter the main problem will be analyzed. The problem analysis is divided in three parts. First we analyze the causes of the product failures, then we quantify them and finally investigate what impact the product failures have on the LCT resp. MLT.

5.1 ERROR ANALYSIS

In order to find all causes of the product failures, we will deal with the following research questions in this section:

- What causes product failures?
    - What are possible reasons for product failures that can occur in the production?
    - Do the errors occur during the manufacturing process or before?
    - Where do most of the product failures occur?

Hopp and Spearman (2000) state the first goal of just in time production is “zero defects” (p.153). Therefore it is essential that every part is made correctly the first time. Quality should not be ensured by the inspection. “Quality must occur at the source” (p.153). This analysis identifies the problems at the source and is based on the data of internal reclamations, which were collected last year (20.05.2014-23.08.2014), observations and interviews made during the three working shifts.

5.1.1 Analysis of the manufacturing steps

In order to see which steps can be possible causes of poor product quality, the following Figure 4 shows a simple overview of the manufacturing processes. If this figure would be compared to Figure 2, it would cover the steps from the “production” until the “shipping”.

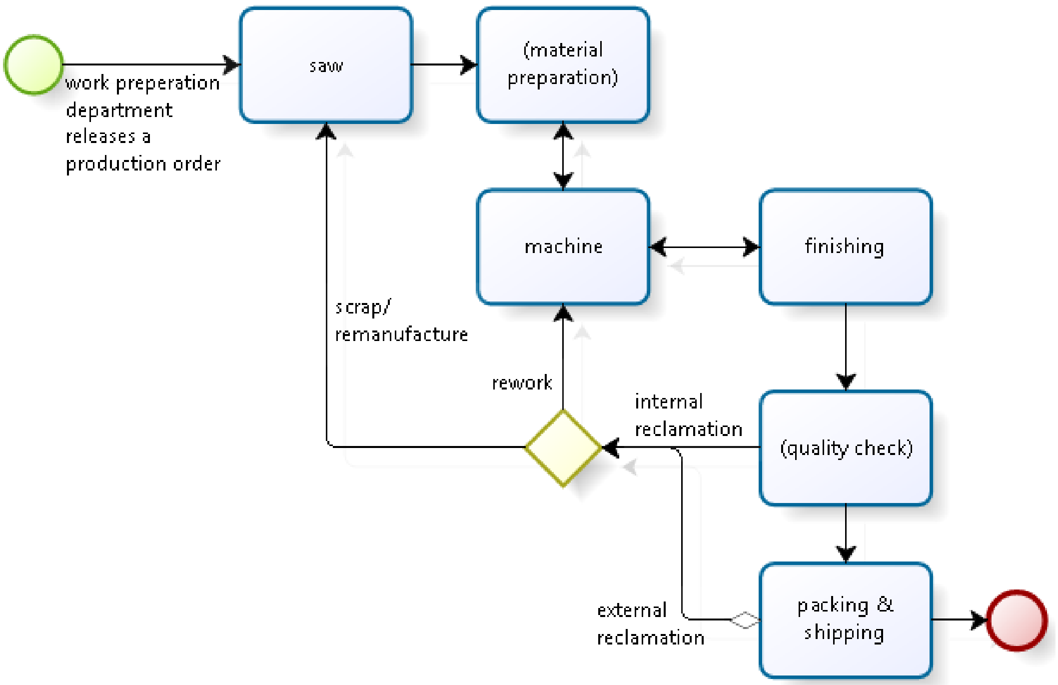


Figure 4: A brief overview of the manufacturing process, including the transport.

The steps which are put into brackets are optional and are not needed for every type of product. The manufacturing process starts with the work department releasing the order. The worker at the saw will get the material and starts working. Sometimes it is needed to plane and to temper the material before it can be processed. Then the material gets to the most important part of the process: the production at the machine. The production consists of 18 CNC-machines. Most of the times one or two machines are needed during the production process. Sometimes the product will be tempered or planed after it was processed at the first machine. After the production the product will usually get some finishing. Most of the production orders have to pass the quality check. In case they do not pass, they return to the production as internal reclamations, which will be either reworked or remanufactured. The same can happen if the customer rejects the order and sends it back as an external reclamation. Of course remanufacturing is worse, since all the steps have to be done all over again. If an order returns as internal or external reclamation it has to pass the quality check before it is sent back to the customer, even though they are likely to be alright.

In order to find all possible errors, which cause the product failures, we will interview employees at these different stations and ask them for possible errors, which can occur at their station or which are caused by other sources inside or outside of the production (e.g. when a production orders lacks preparation). Thereafter we also interview employees and responsible persons outside of the production.

5.1.1.1 Customer orders

The diversity of customers is big therefore also the types of drawings are diverse. Wrong drawings or files can have dramatic effects on the product failure when noticed too late. Normally a customer orders with a printed pdf drawing and a digital drawing (DXF or DWG) of his desired product. The digital drawing can be used for the programming of the machine. Sometimes they also send a 3D file (e.g. step, SolidWorks). This really helps the programmers understand the intention of the customer. The best case is thus a professional drawing with a DXF and a 3D file. In some cases there is no drawing that means that the CAD department has to make the technical drawing as a DFX file which can also lead to errors.

5.1.1.2 Work preparation department

While preparing the production work there are a lot of things which can go wrong. The whole work rotation can be done in wrong sequences. Sometimes steps are forgotten. When tempering is missing, the product is more likely to fail, because tempering reduces the risk of deformation. The work preparation department should make sure that whenever a production order arrives at the saw, the working steps and the drawings are without fault. This is not always the case.

5.1.1.3 CAD department

The CAD department writes new programs for 3 of 18 machines, controls the DXF files for 5 machines (suction plates) and sometimes makes supporting programs for some machines. In some cases they have to make new drawings. Whenever a failure occurs in the drawings or programs, the machine operator will get into trouble. In night shifts this is a big issue, because it cannot be corrected directly at the time. This has a huge effect on the productivity since the series and the big batches are running at night.

5.1.1.4 The purchasing department

When the purchasing department buys material, in few cases it happens that the wrong material or sizes are ordered. Teplast tries to have a little warehouse, thus they do not store a lot of material. Normally one or two plates of the most common material are in stock. Therefore the material is never a long time in stock before getting processed. The reason for this is that Teplast wants to avoid capital commitment. However, plastic can be processed better, if it lies in stock for a longer time, because this will decrease the tension.

5.1.1.5 Saw

At the saw the material can be sawed in the wrong sizes. Sometimes it happens that the wrong material is taken from the storage. The worker at the saw is also responsible for putting the residual material back. When looking at the storage place, it can be noticed that there is messiness and the material is not stored in a proper way. This has bad influences on the material since plastic does deform. Those damages are mostly noticed too late and should not occur in the first place.

5.1.1.6 Machine operator

15 of 18 machines are programmed at the machine. At the CAD department they prepare all the DXF files for the suction plate machine (5). The machine operators have the following possibilities when programming the machine:

- Only using the printed PDF drawing
- Only using the DXF file
    - Prepared DXF
    - Original DXF (which the customer sent)
- Using both

Some operator's prefer to prepare the drawing on their own, because they can do it fast and sometimes there are errors in the DXF files (probably in the non-prepared ones). Moreover, everybody has its own way of programming, so they want to do it themselves. The people working at the quality check assume that the most errors occur, because operators trust the DXF files (even though they are not prepared). They also think that there is an improvement since the CAD department started preparing DXF files for the suction plate machines. If a programming problem occurs the operators always need to go back to the CAD department. Since they are only working from 6.30 until 15.30, they cannot always fix it. If this happens in the night shift, they cannot continue with that batch, thus machine time, operator time and money is wasted.

Sometimes the setup of the machine fails (e.g. wrong tools are used). Actually it is kind of a vicious circle, because wrong setups increase the rework rate and the rework rate increases the amount of setups.

When the product is inserted falsely, the machine cannot mill the product where it is supposed to. Those errors mostly happen at night while producing series. These are simple human errors which happen to new workers or temporary workers.

According to the internal reclamation data, most errors occur, because the products are not checked properly and thus will not be corrected. This can happen due to human sloppiness or laziness. Also temporary or new machine operators might not know how to measure properly. For some series the four-eyes-principles is applied. The 4-eyes-check document can be seen in Figure 13 in Appendix B. After processing 19 parts the 20th, 40th, 60th etc. is checked by two persons. Out of the 353 internal reclamations, 50 random samples were taken to see if there are noticeable problems regarding the piece number and material, which is shown in Table 5 in Appendix C. Out of these 50 there were 3 production orders with a noticeable higher piece number. If the piece number is high, they are series and most likely processed in the night shift. Only for one of these orders the work preparation department determined a mandatory 4-eyes-check, but the control failed anyway. One reason could be that the 4-eyes-check is not taken seriously.

In §4.2 we described that in some companies there are separate lines to manage the rework. Sometimes this is also the case at Teplast. After a defect is noticed at the quality check, the rework sometimes takes place in the finishing department and will be grinded to correct the error. In some cases it is reworked at the same machine but by another machine operator, because by the time the error is noticed, the operator is not working anymore. This is not a good solution, because everybody should be responsible for his own mistakes. Not to punish the people but to create a learning effect.

Finally we can locate the origins of the problems, because during that period the causes of the internal reclamations were analyzed and recorded. In Figure 5 we can see 79% of errors occurred at the machines, which is not surprising, because it is the main manufacturing part.

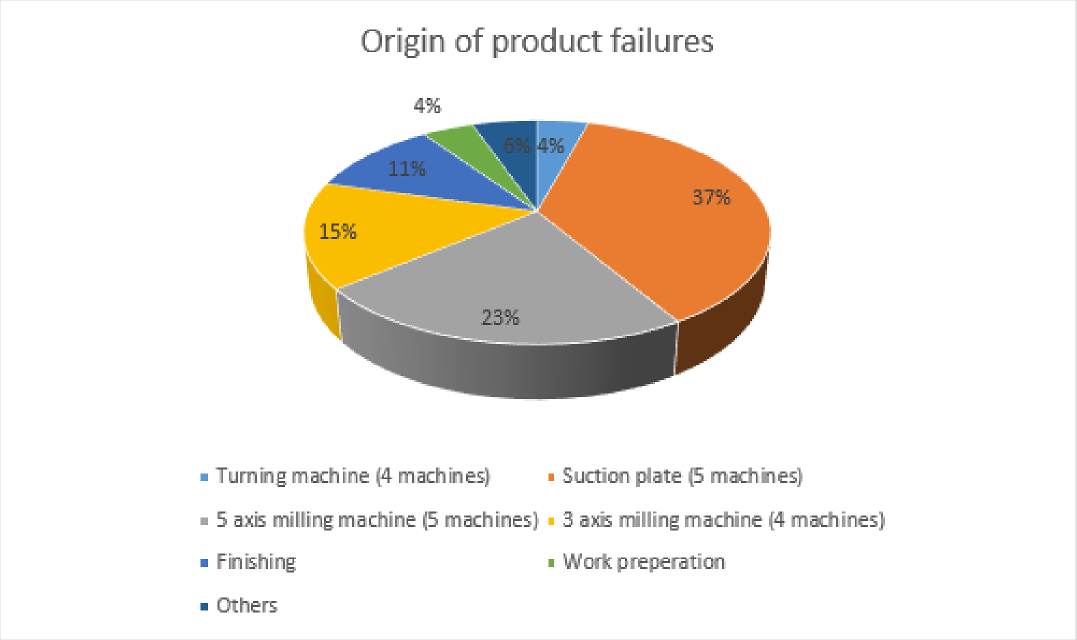


Figure 5: A pie chart, showing the fractions of where the errors occurred.

Noticeable are the five suction plates with 37% product failures. The big advantage of these suction machines is that less setups are necessary. The product can be put in there once and it can be milled roundly. These machines can be categorized as 3 different types, as three are the same type. Taking a closer look at the suction plates we can also detect that one type of machine is conspicuously higher than the others.

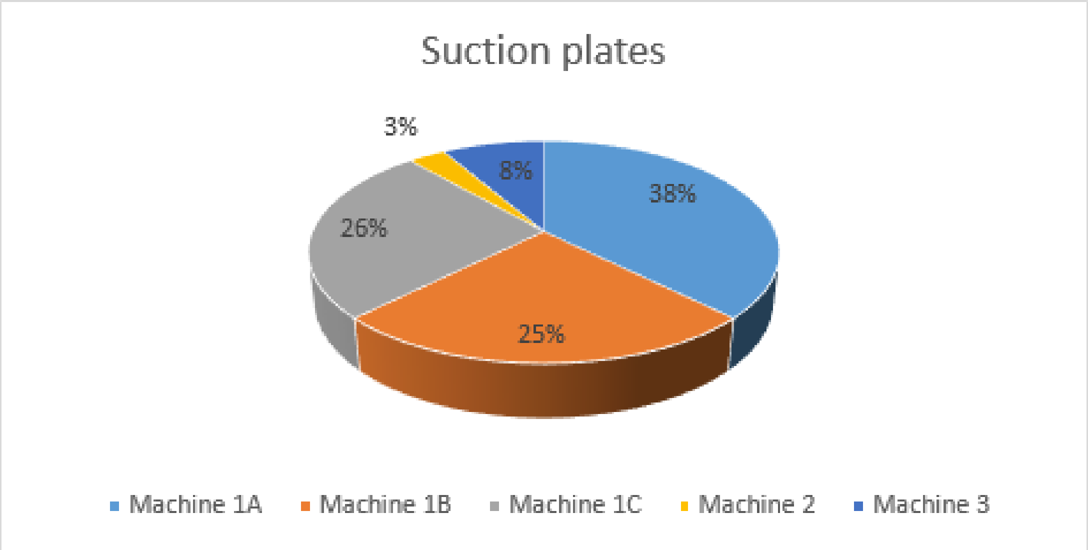


Figure 6: A pie chart, showing the fractions at which suction plate the most errors occur.

The reason could be that during the last year a lot of new people were hired and most of them started working at M1 (1A, 1B or 1C). Also many production orders start at M1. The production orders which are aligned to M1 will be called M1 production orders and will play a key role in §5.2 and finally in §7.

5.1.1.7 Finishing

In the finishing area a lot of processes (e.g. deburring) are much alike. It can happen that there is a 100-product batch and all edges have to be deburred. After this batch a similar product arrives, but one edge is supposed to remain sharp. In most of these cases all edges of the new product will also be deburred even the one which was supposed to remain sharp. If the processes are that much alike, it can easily happen that a worker assumes the following will be the same processed the same. Furthermore not all workers can read technical drawings, thus will not know either.

5.1.2 Other observations

While observing the production process some general problems were detected.

5.1.2.1 Miscommunication

There is a lot of miscommunication and not feeling responsible for own mistakes among operators and departments. Lean manufacturing is based on working together and having a common vision (Symbol BV, 2014). The programmers lack feedback from the machine operators. The sales department is focused on selling products and does not always check with the limits of the production. For instance, a lot of people are going on holidays, which reduces capacity. Therefore less orders should be accepted, but due to insufficient communication that does not happen. Regulating the WIP is of big importance (see §4.2.3). The higher the WIP, the higher the amount of mistakes and the longer the LCT.

5.1.2.2 Motivation

During talking to the employees it became clear that it is not that important to them how efficient they work. They get paid for eight hours a day and that is their motivation. This decreases the creative input from the employees. On the other hand there is no audience for their ideas. For instance, the workers said they can work better with material, which has been in stock for a longer period, instead of using material, which has just yet arrived from the supplier. This was communicated to the work preparation department and they reported it to purchasing and sales department. But they do not want a lot of material in stock, because of capital commitment. As Abraham Maslow (Boddy, 2011) stated, recognition is an important factor of motivation. If the worker's input is not recognized and nothing changes, the motivation will decrease.

5.1.2.3 Material failures

Since plastic is also affected by temperature and inner tension, the material can deform and thereby not pass the quality check. Especially during the summer, this material distortion is a big problem, because the machine operators check the product in the production hall while there is a temperature of e.g. 35 °C and the quality check is made in a separate room with 20 °C. Plastic changes with temperature.

Also every material is different. In Table 5 and 6 in Appendix C the material was analyzed and some peculiarities were seen. Out of 50 random samples of the 353 internal reclamations (Table 5) and 71 external reclamations (Table 6), the most important materials were:

- 31 PE (polyethylene)
    - 24 PE 1000
    - 7 PE 500

- 30 POM (polyoxymethylene)
    - 16 natural
    - 13 black
    - 1 blue
- 11 PEEK (polyetheretherketone)

The most production failures occurred with the two materials: PE and POM. They have a percentage of 25.6% and 24.8% (regarding the total of 121). The last one has a just 9%, but it is expensive material and therefore important to mention. As mentioned in §5.1.2.2 the longer the material is stored, the easier workers can process the material, because the tension reduces. Maybe we can trace back these material problems to the fact that Teplast, does want to have a big stock of material and buys the material most of time on short term.

5.1.3 Conclusion

In the errors analysis we interviewed employees to find all possible causes of errors that can occur at the production stations or before. We find that errors can have all kind of causes. The most common product failure occurs, because the workers did not check properly the product at the machine or maybe not early enough. New material also influences the amount of failures, because new material is more likely to cause material failures. Some orders also lack preparation, which can also be caused by poor drawings of the customer. We realized that 79% of the errors occurred at the machines, which is normal, because it is the main part of the manufacturing process. Especially the five suction plates attracted attention with 37% of product failures have occurred there. Of these suction plates three machines with the same type (M1) stood out, because of all product failures at the five suction plates, 89% occurred at the three machines with type M1. Therefore, we will focus on M1 production orders, when we quantify the product failures (see §5.2) and the impact of them on the MLT (see §5.3).

5.2 QUANTIFYING THE PROBLEM

In this section we will answer the following research questions:

- How many products do fail (scrapped and defective products) and what is the percentage?
    - Internal reclamations?
    - External reclamations?
    - Not reported errors?

Based on the errors analysis in §5.1, we will quantify the amount of product failures, which occurred at M1. Product failures can be detected at the end of the production line or after a production step before the end. In this context end of the production line means either the quality check or the customer. There are a lot of failed products, which are detected and fixed during one of the production steps, before they reach the quality check or the customer. Teplast does not report these failures and they are difficult to measure. One order consists out of one or more order lines. Every order line is one production order and consists of a certain amount of pieces. Whenever there is one failed product, the order cannot be sent. For example out of 500 products there is one, which is broken, then this one will be remanufactured and the order can be sent whenever all pieces are done. There are just a few exceptions of partial deliveries. Usually it is the case that whenever there is one broken product, they are all broken. Order lines however, can be delivered separately. If there is one order with 20 order lines and a failure occurred in one of those, the other 19 will be sent way to the customer. Therefore the actual amount of the broken pieces is not that important rather the amount of times one M1 production order (respectively one order line) cannot yet be delivered due to poor products quality. Therefore, we need to find out the percentage of M1 production orders that return to the production as internal reclamations, because products are either scrapped (p_{S_I}) or defective (p_{D_I}), or as external reclamation, because products are either scrapped (p_{S_E}) or defective (p_{D_E}). We will also measure the fraction of production orders, which are delivered to the customer with good product quality p_G.

5.2.1 Internal reclamations

From the data of the internal reclamations we find that 353 production orders were categorized as internal reclamations during that period (20.05.2014-23.08.2014). This amount can be brought into relations by checking how many orders were produced in the same period.

353 internal reclamations/3349 production orders = 10.5%

We find an internal product failure rate of 10.5%, but because it was seen that the three machines of type M1 have a noticeable high amount of errors we will focus on the M1 production orders. Out of these 353 internal reclamations 132 occurred at machine 1. So this numbers needs to be compared with the amount of M1 production orders in that period and not to the total. Since we cannot manually analyze 3349 production orders, to find out how many M1 production orders there are, we will take 75 random samples and count the number of M1 production orders. The outcome is 33 of 75, thus 0.44. This factor will be called z. It seems odd that 44% of all production orders have to pass M1, even though these machines are 17% of all machines. We validated the correctness of this outcome with the work preparation department. Therefore the sample number of 75 will be taken as representative. The product of z and the 3349 is 1473.6.

Therefore the new percentage will be:

132 M1 internal reclamations/1473.6 M1 production orders = 7.9%

The percentage is decreasing, because the factor z is that high (higher than the amount of product failures at M1). So 7.9% of the M1 production orders will be categorized as internal reclamations. Whenever this happens there are 3 options:

a) Remanufacturing (scrapped product)
b) Rework (defective product)
c) product will be sent without adjustment (even though the measurements were not perfect, it is sufficient for the customer)

The distribution regarding the M1 production orders is shown in Figure 7:

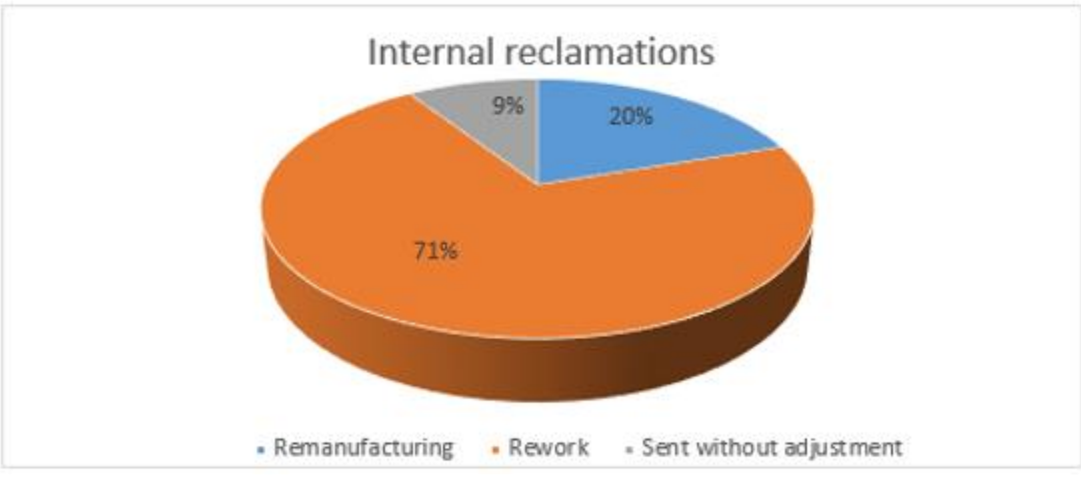


Figure 7: A pie chart, showing the fractions of internal reclamations, which need to be remanufactured, reworked or are sent without adjustment.

The probability that there are M1 production orders with scrapped or defective products which internal reclamations is therefore:

p_{S_I}= (26/1473.6) = 1.8%

p_{D_I}= (93/1473.6) = (255/3349) = 6.3%

5.2.2 External reclamations

All of the external reclamations are reported in the "Aupos" system. We will look up the number of external reclamations of the same period compare it with the production orders (including all, also reworked and those, which were sent without adjustment):

23 external reclamations/1473.6 production orders = 1.6%

In Figure 8 the percentage of remanufacturing and rework is shown.

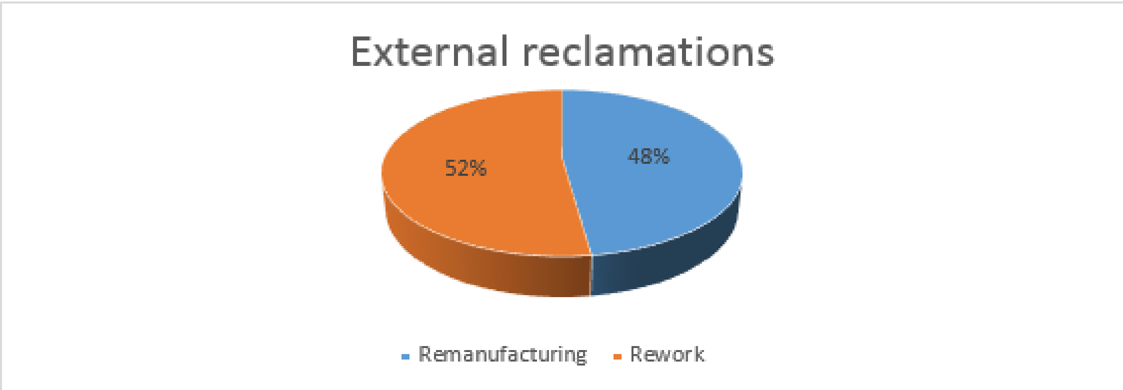


Figure 8: A pie chart, showing the fraction of external reclamations, which need to be remanufactured or reworked.

Therefore we can calculate the probability as we did for the internal reclamation:

p_{S_E}= (11/3349) = 0.8%

p_{D_E}= (12/3349) = 0.8%

As shown in Figure 9 this leads to a total percentage of detected product failures of 9.64%, which consists of 8,08% internal (not regarding the jobs which are sent anyways) and 1,56% external reclamations.

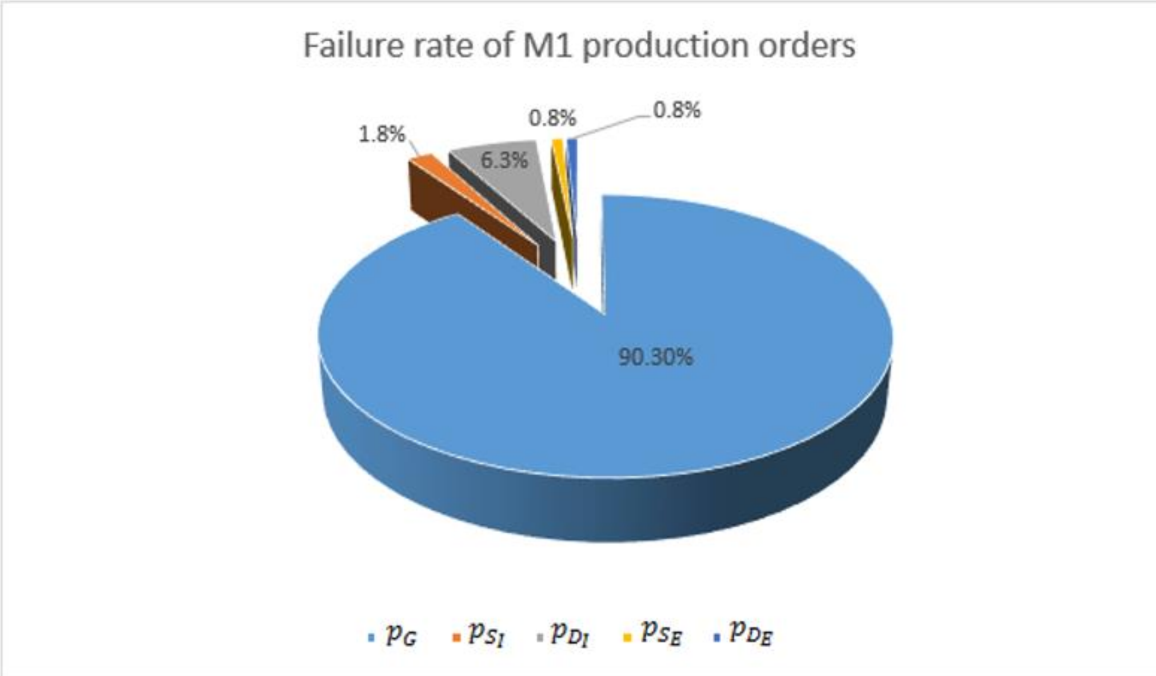


Figure 9: A pie chart, showing the fraction of product quality of M1 production orders, detected (internally or externally) as good, scrapped and defective.

It is clear that that external reclamations are much worse compared to internal reclamations, because they include transportation time and lead to bad reputation. These are only the numbers of products which run through the whole process and are detected at the end of the production line.

5.2.3 Conclusion

Finally we can quantify the problem regarding the M1 production orders. The rework rates were less than expected, because the factor z, which indicates the fraction of M1 production orders in proportion to the total amount, was surprisingly high. The fact that the factor z is 0.44 explains that most failures occur at machine M1. This could also lead to a high working load at M1. We find the following product failure rates: p_{S_E}= 0.8%, p_{S_I}= 1.8%, p_{D_E}= 0.8% and p_{D_I}= 6.3%. Consequently there are 90.3% M1 production orders, which are delivered to the customer with a good product quality (p_G= 90.3%). We cannot establish the total amount of failed products, because we miss the data of failed products, which are fixed before the quality check. Teplast does not report these product failures.

5.3 Impact of the problem

We have come to the last section of the analysis, where we will answer the following two research questions:

- What impact does the product failure rate have on the current MLT?
  - What could be the MLT, if the failure rate improved?

As we already mentioned in §4.1 we do this by computing the line cycle time and show the influence of poor product quality on the LCT. In this analysis we will only use the M1 production orders. One job is hence equal to one M1 production order, which could also be a batch of 20 products. The arrival and processing rates are determined per operating hour with a working shift of 8 hours a day. The shifts will be important for the calculation (see §5.3.2), because there is one working station (the machine) that does more than one working shift per day.

5.3.1 Collecting data

In order to calculate the line cycle time a lot of information is needed (see §4.1):

The possibilities that the product quality is either scrapped or defective and is therefore sent back to production as an external or internal reclamation = $p_{S_E}, p_{S_I}, p_{D_E}, p_{D_I}$ (which have been quantified in §5.2)

The external arrival rate per hour= γ_E

The SCV of external arrival rate at station 1= C_{a01}^2 (production orders always arrive at station 1 first):

The different working stations= i = 1, …, 15

The number of servers at station i= c_i

The average natural process time at a station= t_{0i}

The SCV of the process times at station i= C_{si}^2

The transition probabilities that a job goes from station i to station j= P_{ij}

<u>Arrival rate γ_E</u>

To compute γ_E we take the number of orders arriving at Teplast in four weeks (02.03-27.03.2015) which was 1075. Dividing 1075 by four (amount of weeks) and by 5 (amount of working days) and by 8 (amount of working hours every day, we get γ_T = 6.72 the arrival rate per hour. The calculation are based on a working day of 8 hours. 6.72 would be the total amount of production orders arriving per hour. As the focus is on M1 machines, the total amount γ_T has to be multiplied by the factor z, which is the fraction of M1 production orders. The product of z and γ_T is γ_E=2.96.

<u>The SCV of external arrival rate C_{a01}^2:</u>

With the same data we can see how many jobs arrive in those four weeks: 61.2, 57.4, 45.2 and 56.6. Since all production orders are arriving at station 1, we only focus on the external arrival rate at station 1. For this purpose we can apply Ross' formula here: $C_{a01}^2 = \frac{\sigma^2}{t}$ (Ross, 2014). This formula only works for large values of time buckets and not for small ones, that is why we use weeks here and not hours or days. The outcome of the variance of the data σ^2 is 35.69 and mean t is 55.1. Therefore C_{a01}^2 is 0.65.

The rest of the data is collected from the 33 M1 production orders, which were also used to determine z. A higher number would give better approximations, but the data could only be analyzed manually and therefore it was a lot of work. However, the focus lies on showing the impact of product quality on the LCT, therefore the data is satisfying for this analysis.

<u>Stations i:</u>

For these 33 productions orders we find 15 different stations. Compared to Figure 4 (see §5.1) this description of the working stations is much more precise, but they have the same start and ending. All production orders start at the saw and finish with the packing resp. the delivery to the customer.

1. Saw
2. Face milling
3. Planing
4. Tempering
5. Machine 1 (A,B,C)
    a. First
    b. Second

c. Rework
6. Flush milling
7. Drilling
8. Chamfering
9. Other milling machine (no suction plate)
10. Turning machine
11. Inserting nut
12. Deburring
    a. Normal
    b. Extra
13. Marking
14. Quality Check
    a. Normal
    b. After rework
15. Packing

Out of these 15 stations we split up three stations. Even though they are the same stations, we deal with different processes. For example there are three options why a job gets to station 5 (machine 1A, 2B, 3B): first time being processed at M1 (all M1 production orders), second time being processed at M1 (some M1 production orders) and the production orders which return to the machine, because they have to be reworked. Deburring usually takes place at the end of the production but some jobs need extra deburring in between the production. There are two times of quality check, because the jobs which are already being reworked will normally pass the quality check without going back to the production. Production orders which were categorized as scrapped have the same percentage of failing again, since the start all over at the first station.

<u>Server c_i</u>
With data of the working schedules, we get the number of employees working at a station. Sometimes there is a group of people, which is responsible for different working stations. For example there are 4 people working at station 2, 6, 7, 8, 11. These stations will be considered as shared stations and later on in the calculation, they will be regarded as one station and be named after the last station. Therefore there will be only 10 stations (shared stations in bolt): 1,3,4, **5* (5a,5b,5c)**, 9, 10, **11* (2,6,7,8,11)**, **13* (12,13)**, **14* (14a,14b)**, 15. The amount of employees working at a station is defined as c_i.
There are 5 suction plate machines: 1A, 1B, 1C, 2, 3. This analysis is focusing on the three machines of type M1. Hence, c_5 should be 3, but because in busy times the other two suction plate machines "help out", we have to increase c_5. Based on discussion with the work preparation department, we estimate that 25% of operating time of the other two machines is used for M1 production orders. Therefore, we increase the capacity of the M1 machines by 0.5 (0.25*2) and get c_5=3.5.

<u>Process time t_{0i}</u>
Since there is no data of the effective process time, we will use estimations from the work preparation department. For this reason we use the raw process time t_{0i}. At some stations this time is missing (saw, quality check, packing). After talking to the employees an estimation was made for these stations as well. The process time was already defined in §2.2.1 as the "required time to process a part at a station, i.e., excluding possible extra waiting" (Hopp & Spearman, 2000), therefore the process time can also be described as:

$$\boxed{\text{Process time} = \text{move time} + \text{setup time} + \text{processing time} + \text{checking time}}$$

We will use the station process time as the time a batch needs to go through these steps. If there is a batch of 20 products, regardless of the waiting times the batch as whole is first moved to the station, then the station will be setup for this particular batch and type of products. The processing time and the checking time depend on the batch size, because these two steps have to be done 20 times. Therefore the batch size was used for the calculation of the average process time but in the following the batch size will not be a part of the calculations. To compute the process time, we can take the average process times from the production order. The shared stations will already be regarded as one. That is why we take the average of all the process times of the included stations to determine the process time t_{0i}. The process times are defined in hours. The production rate μ_i is the reciprocal of the process time.

The SCV of the process times C_{si}^2:

We can calculate the SCV of the process times by using the formula $C^2 = \frac{\sigma^2}{t}$. Since the shared stations, will be regarded as one, we include the variability of different processes, when they are done by the same group of people. After computing C_{si}^2, we can show all data now in Table 2:

i	c_i	t_{0i}	μ_i	C_{si}^2
1	1	0.11	9.22	0.25
3	1	0.09	11.11	0
4	1	0.06	16.67	0
5* (5a,5b,5c)	3,5	2.00	0.50	1.32
9	1	0.99	1.01	0
10	1	3.17	0.32	0
11* (2,6,7,8,11)	4	0.16	6.22	2.54
13* (12,13)	8	0.45	2.23	2.08
14* (14a,14b)	2	0.20	5.00	0
15	2	0.17	6.00	0

Table 2: This table shows the data of each working station.

Probabilities P_{ij}

In the following Figure 10 all working stations and routing probabilities are shown. As already said in §4.2 we are dealing with a Markovian routing. "A Markovian routing is characterized by the routing matrix P, where element P_{ij} denotes the probability that a job leaving station i has its next operation at station j, i, j = 1, ..., M." (Zijm, 2003, p.38).

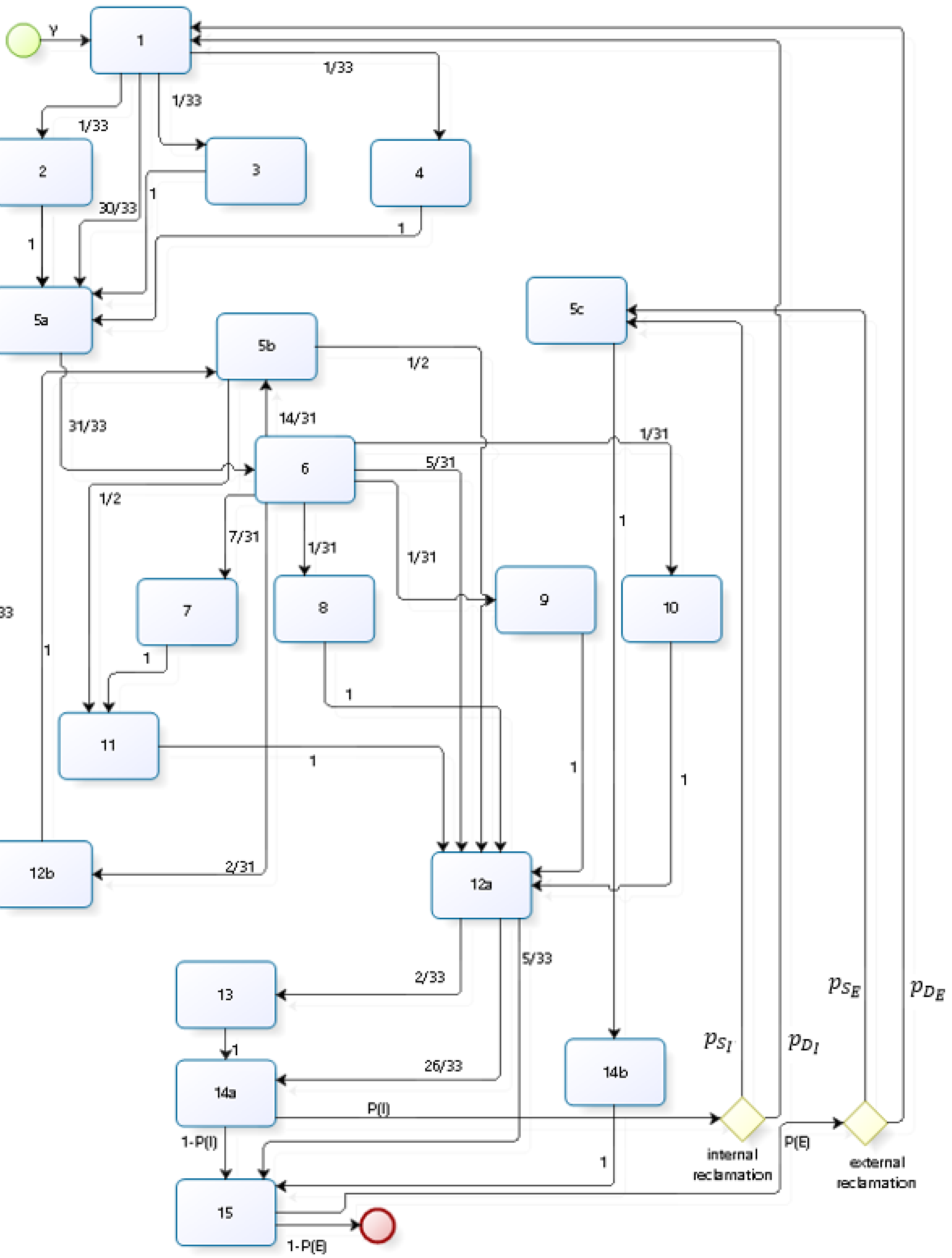


Figure 10: Queueing Model

5.3.2 Calculation

The outcome of the 19 equations, which can be gathered from the Figure 12, will be the traffic (internal and external) at every station, determined as λ_i.

$\lambda_1 = \gamma_E + \lambda_{14a} * p_{S_I} + \lambda_{15} * p_{S_E}$

$\lambda_2 = \frac{1}{33}\lambda_1$

$\lambda_3 = \frac{1}{33}\lambda_1$

$\lambda_4 = \frac{1}{33}\lambda_1$

$\lambda_{5a} = \lambda_1$ (every order from the saw passes this station once)

$\lambda_{5b} = \frac{14}{31}\lambda_6 + \lambda_{12b} = \frac{18}{33}\lambda_1$

$\lambda_{5c} = \lambda_{14a} * p_{D_I} + \lambda_{15} * p_{D_E}$

$\lambda_6 = \frac{31}{33}\lambda_1$

$\lambda_7 = \frac{7}{33}\lambda_1$

$\lambda_8 = \frac{1}{33}\lambda_1$

$\lambda_9 = \frac{1}{33}\lambda_1$

$\lambda_{10} = \frac{1}{33}\lambda_1$

$\lambda_{11} = \frac{1}{2}\lambda_{5b} + \lambda_7 = \frac{16}{33}\lambda_1$

$\lambda_{12a} = \lambda_1$ (every order from the saw passes this station once)

$\lambda_{12b} = \frac{2}{31}\lambda_6 + \frac{2}{33}\lambda_{5a} = \frac{4}{33}\lambda_1$

$\lambda_{13} = \frac{2}{33}\lambda_1$

$\lambda_{14a} = \frac{26}{33}\lambda_{12a} + \lambda_{13} = \frac{28}{33}\lambda_1$

$\lambda_{14b} = \lambda_{5c} = \frac{28}{33}\lambda_1 * p_{B_I} + \lambda_{15} * p_{B_E}$

$\lambda_{15} = \frac{5}{33}\lambda_{12a} + (1 - p_{S_I} + p_{B_I}) * \lambda_{14a} + \lambda_{14b} = \frac{5}{33}\lambda_1 + (1 - p_{S_I} + p_{B_I}) * \frac{28}{33}\lambda_1 + \frac{28}{33}\lambda_1 * p_{B_I} + \lambda_{15} * p_{B_E}$

Except for the fixed variables $p_{S_E}, p_{S_I}, p_{B_E}, p_{B_I}$ and γ_E all λ_i are now depending on either λ_1 or λ_{15}. Solving the last equation leads to

$\lambda_{15} = \lambda_1 * s$, being $s = \frac{1-\frac{28}{33}p_{S_I}}{1-p_{D_E}}$.

Finally we get

$\lambda_1 = \frac{\gamma_E}{1-\frac{28}{33}p_{S_I} - s * p_{S_E}}$

and can compute all other λ_i for $\gamma_E = 2.96$, $p_{S_I} = 0.0176$, $p_{D_I} = 0.0631$, $p_{S_E} = 0.0075$ and $p_{D_E} = 0.0081$ (as computed in §5.1).

Normally ρ_i is defined by this formula: $\rho_i = \frac{\lambda_i}{c_i * \mu_i}$. But because of Teplast situation, we will add another variable to get: $\rho_i = \frac{\lambda_i}{c_i * \mu_i * \alpha_i}$. The reason is that we have to take into account that the traffic at station λ_i is only allotted to M1, but in general the stations are also used for other production orders other than M1. Therefore the stations cannot have full capacity for these M1 orders.

Therefore at all stations the variable α_i will equal to z = 0.44, except for station 5, which is M1 and therefore only allotted to M1 production orders. But M1 is actually processing 24 hours, three shifts a day and the others only 8 hours. The working load can be done in three shifts, instead of one, therefore α_5 is equal 3.

Now we are still missing the SCV of interarrival rate C_{ai}^2. In order to apply the formulas as described in §4.1, we need to aggregate the routing probabilities P_{ij}, since we have to consider the shared stations as one station. Therefore we take probabilities from Figure 10 and aggregate them with the traffic intensity at every station λ_i. For instance station 9 has only jobs coming from station 6, but station 6 is no longer station 6 but is merged in station 11*. That is why we take the fraction of traffic intensity at station 6 λ_6 compared to traffic intensity at station 11* λ_{11*}, which includes station 2, 6, 7, 8, 11 and we get 0.55. By multiplying this number by the old $P_{6\,9}$, which is 1, and we get the new $P_{11\,9}$ equal to 0.55. Like this we can aggregate all probabilities P_{ij} and can apply the formulas from §4.1 and get the following equations:

$$C_{a1}^2 = 0.30$$

$$C_{a3}^2 = 0.97 + 0.03 * C_{a1}^2$$

$$C_{a4}^2 = 0.97 + 0.03 * C_{a1}^2$$

$$C_{a5*}^2 = 0.48 + 0.22 * C_{a1}^2 + 0.02 * C_{a3}^2 + 0.02 * C_{a4}^2 + 0.01C_{a13*}^2 + 0.05C_{a11*}^2$$

$$C_{a9}^2 = 0.82 + 0.04 * C_{a11*}^2$$

$$C_{a10}^2 = 1.08 + 0.02 * C_{a11}^2$$

$$C_{a11*}^2 = 0.96 + 0.03 * C_{a11*}^2 + 0.04 * C_{a5*}^2$$

$$C_{a13*}^2 = 0.91 + 0.2 * C_{a11*}^2 + 0.02 * C_{a13*}^2 + 0.01 * C^2{}_{a9} + 0.01C_{a10}^2$$

$$C_{a14*}^2 = 0.56 + 0.62 * C_{a13*}^2$$

$$C_{a15}^2 = 0.47 + 0.38 * C_{a14*}^2 + 0.01 * C_{a13*}^2$$

Solving these equations we finally get the following values for $C^2{}_{ai}$:

i	C_{ai}^2
1	0.3
3	0.98
4	0.98
5*	0.65
9	0.86
10	1.1
11*	1.02
13*	1.15
14*	1.27
15	0.97

Table 3: This table shows the SCV of the interarrival rates at each working station.

Now we have all the data to apply the formulas as described in the literature research to compute CT_i:

$$CT_i = \frac{\rho_i^{\sqrt{2(c_i+1)}-1}}{\mu_i c_i (1-\rho_i)} * \frac{C_{ai}^2 + C_{si}^2}{2} + \frac{1}{\mu_i}$$

Afterwards the total CT of all 10 stations can be calculated with the following formula:

CT = $\sum_{i=1}^{M} V_i * CT_i$

Table 4 shows the outcome of these formulas:

i	λ_i	c_i	α_i	μ_i	ρ_i	C_{si}^2	C_{ai}^2	CT_i	V_i	$CT_i * V_i$
1	3.02	1.00	0.44	9.22	0.75	1.00	0.3	0.20	1.02	0.20
3	0.09	1.00	0.44	11.11	0.02	1.00	0.99	0.09	0.03	0.00
4	0.09	1.00	0.44	16.67	0.01	1.00	0.99	0.06	0.03	0.00
5*	4.86	3.50	3.00	0.50	**0.93**	**1.32**	0.72	8.74	1.64	14.37
9	0.09	1.00	0.44	1.01	0.21	1.00	0.86	1.10	0.03	0.03
10	0.09	1.00	0.44	0.32	0.66	1.00	1.1	6.56	0.03	0.20
11*	5.13	4.00	0.44	6.22	0.47	**2.54**	1.02	0.19	1.74	0.32
13*	3.57	8.00	0.44	2.23	0.46	**2.08**	1.15	0.46	1.21	0.56
14*	2.75	2.00	0.44	5.00	0.63	1.00	1.27	0.29	0.93	0.27
15	3.00	2.00	0.44	6.00	0.57	1.00	0.97	0.21	1.02	0.21
CT										**16.23**
Tempering								100.00	0.03	**3.10**
Transportation								24.00	1.02	**24.38**

Table 4: This tables shows the previous collected data, plus the calculations made by using the formulas above.

Noticeable in Table 4 is the utilization at station 5 ρ_5 (marked bolt), which is the machine. The workload is really high, which can be caused by low production rate, low capacity or high traffic. Furthermore we encounter high levels of variability of process times (see C_{s5*}^2, C_{s11*}^2, C_{s13*}^2). But only the variability of machine 5 has a huge impact on the LCT if we look at the last column of Table 4. This variability is especially caused by the high variation of batch sizes, which depend on the customer's orders. Therefore it is difficult to lower this variability.

Regarding the impact of the core problem and the expectation of the LCT, we finally get the CT of the first 10 stations, which is 16.23h. But we also want to include the time that the job spends in the tempering machine and the time it is sent to the customer. Therefore we add two more stations with a fixed CT of 100 and 24 hours, and multiply those with the visit rate V_4 (tempering) and respectively V_{15} (packing). To determine the LCT in days the CT of the first 10 stations has to be divided by 8, because the calculations are made on working day basis of 8 hours. The tempering and transportation time has to be divided by 24, because they are not depending on working shifts. The sum is 3.17 days, which does not fit the estimation of the working department, which was 5 to 10 days, but this is not surprising, since only the 33 M1 production orders, were used for the calculation and the models can only give approximations. But the models can be used to give an indication, to what extent the LCT is affected when product quality is improved. If the product quality, which was measured with product failure rates $p_{S_E}, p_{S_I}, p_{D_E}, p_{D_I}$, was improved (decrease of failure rates), the LCTs decreases as shown in the following Figure 11 and 12. When the product failure rate reduces, the probabilities of the routing change and therefore also the interarrival rates and their variability.

Consequently we have to calculate new C_{ai}^2 for the changed product failure rates. These new values for C_{ai}^2 are shown in Appendix D.

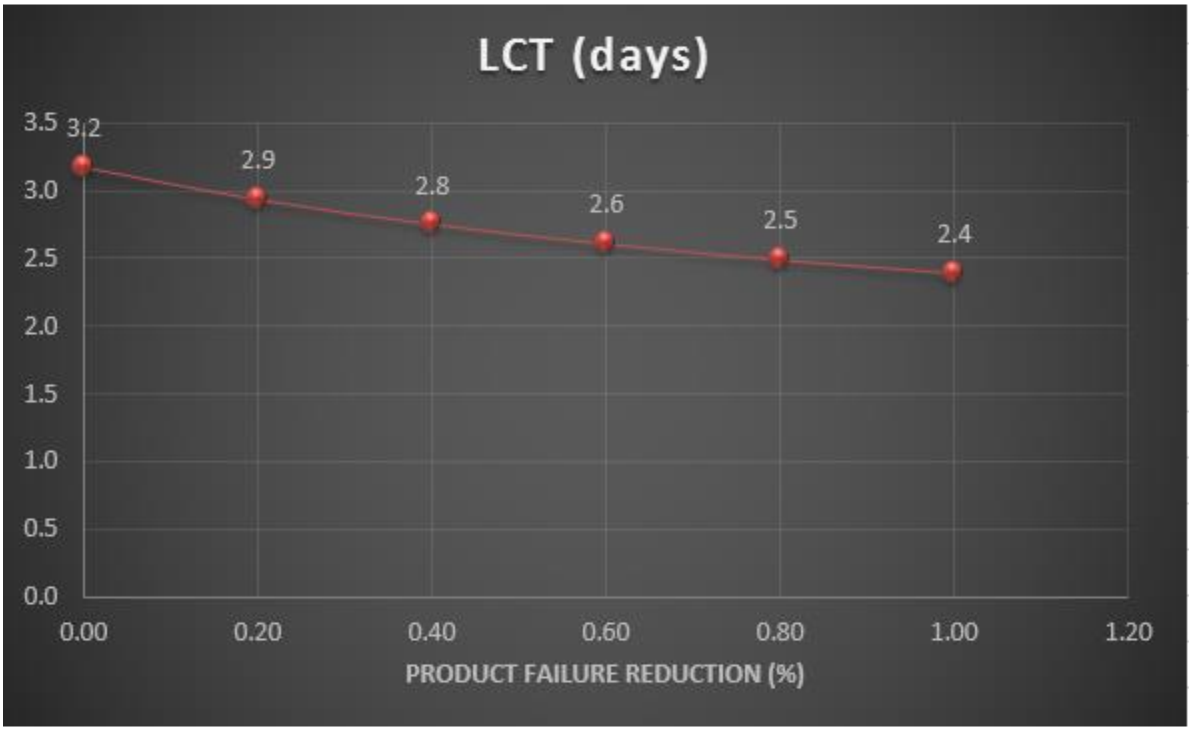


Figure 11: A chart, showing the LCT in days in relations to the product quality improvement.

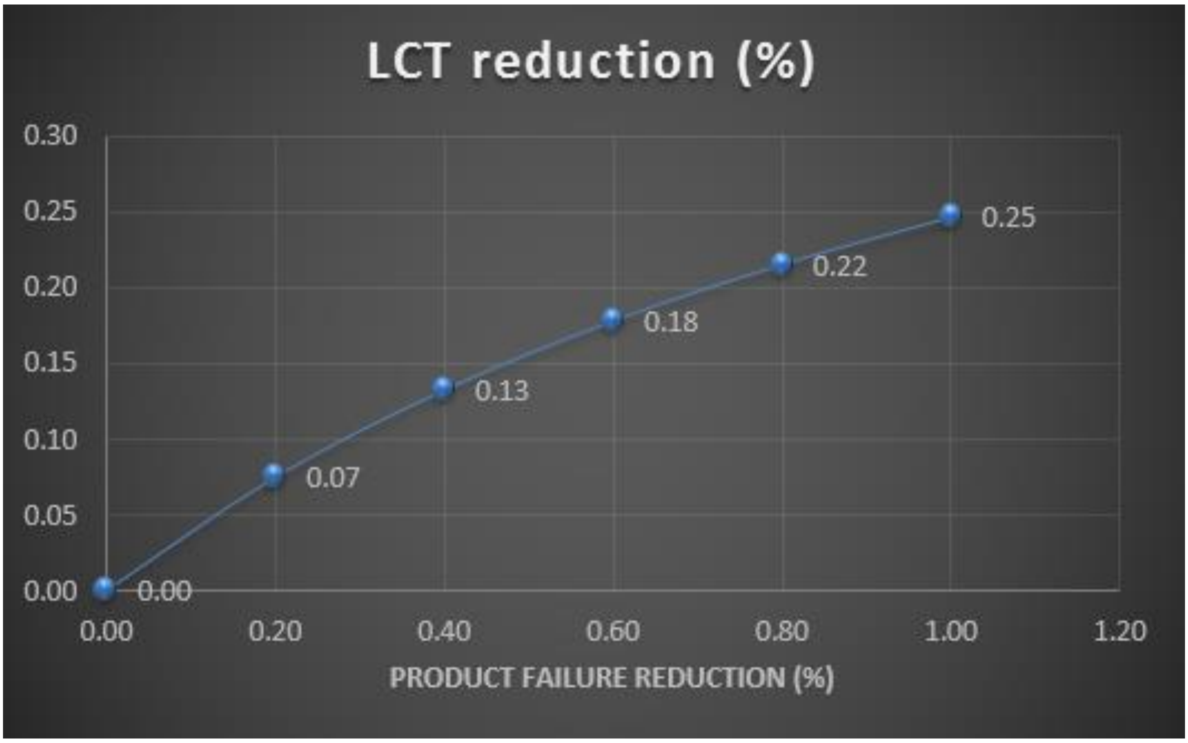


Figure 12: A chart, showing the LCT reduction in percent in relations to the product quality improvement.

Without regarding the costs of poor product quality, these figures show, that with better quality the LCT can be reduced. If for instance Teplast's product quality improved by 20%, the LCT would be reduced by 7%. However, we must not forget we did not imply the product failures that occur during the production, therefore we can assume that the impact would be even higher resp. better.

5.3.3 Conclusion

The results of the impact analysis are presented in Table 4 and Figure 11 and 12. In Table 4 all CTs are calculated with a final outcome of the LCT of 3.1 days. The LCT was used to give an indication of the MLT, since the MLT is a managing variable. The LCT in days and the reduction in percentage are shown in Figure 11 and 12, in relations to the product quality improvement. For instance if the product quality was improved by 20%, the LCT would be decreased by 7%. It was also shown that the work load at three suction plates (M1) is really high. Improving the product quality would lower the traffic and increase the capacity. Alternatively Teplast could also buy an extra machine, which would obviously be a very costly alternative.

6 GENERATION OF ALTERNATIVES TO IMPROVE PRODUCT QUALITY

We have seen that better product quality does reduce the LCT and proven that less rework reduces the PV (see §2.2.3). In §5.3 we determined that product failure do effect the LCT resp. MLT, but still missing are alternatives to improve the current situation at Teplast and to reach a lower product failure rate. For this purpose we will answer the following research questions in this chapter:

- How can Teplast reduce the product failure rate (qualitative)
    - What are the advantages and disadvantages of possible ideas?
    - Can we apply these ideas to Teplast's situation?

The following ideas are based on interviews with employees, literature research and own observation. These are general suggestions to improve the product quality, i.e. reduce the product failure rate and not only applicable for M1.

6.1 INTEGRATED QUALITY CHECK

As we discussed in §4.2.1.1 checklists can be used to prevent human errors of sloppiness and to detect problems immediately at the source. Whenever a machine is used the work preparation puts a paper to the production order where the machine operator can write down his measurements. There should be some extra lines, which can be used in case the work preparation department or the CAD programmers think something is important to pay attention to. After the <u>first</u> product is done (even though there is just one), the machine operator will write down the expected and realized measurements and will also tick off the extra points, in case that the work preparation department or the CAD programmers wrote something down. If the measurements show errors, the machine operator will fix them or will ask for support. If he has to fix them, he has to measure the next one, too. He does not have to write it down, but he should continue until the measurements are good. In that way the error will be fixed immediately. As mentioned in the literature research, introducing a checklist will bring more standardization in the controlling process, because sometimes it is controlled properly, sometimes not. Afterwards another operator should also control it, because when watching at a technical drawing one can get blind for own mistakes. That was experienced by a lot of machine operators. For that reason the four-eyes-principle should by applied here as Teplast already does it for order lines with big batch sizes (see §5.1.1.6). Finally both would have to sign it. The signing prevents the problem of avoiding responsibility and motivates the operators since their errors will be traceable. To this option there are two alternatives: 1) This option can be applied for every product of the batch or 2) just for the first and last one (N=2 Method).

Benefit: Better quality and learn process (self-improvement), machine operator takes responsibility

Drawback: little more time is needed (work department and machine operator), workers might not appreciate this kind of checklist, because they feel controlled

6.2 QUALITY CHECK OF DRAWINGS

This alternative would need an extra worker what makes it a costly alternative. That worker would be only responsible for checking all new customer's drawings and prepare the DXF files for the machine operator. Therefore that person needs to know how the milling and programming at the machine works. The intention is to decrease the preparation time and therefore increase the runtime of the machine and to create quality at source (see §4.2.1). A downside can be that it takes away the working satisfaction of the machine operators, since the programming is considered as the "fun" part of the work.

Benefit: Better quality, less setup time (preparation time), more machine runtime

Drawback: not appreciated by machine operators (less working satisfaction), costs of a new employee

6.3 WORK PREPARATION FOR THE FINISHING

In the finishing area there are a lot of orders with the same working procedure (e.g. deburring). It can happen that there is a 100-product batch and all edges have to be deburred. After this batch a similar product arrives, but one edge is supposed to remain sharp. In most of the cases all edges of the new product will also be deburred, because it is more or less the same process. Besides, not all workers there can read technical drawings. That is why the work preparation should put a (red) remark on the production order (e.g.: "Do not deburr all edges").

Benefit: better quality

Drawback: little more work preparation

6.4 ACHIEVEMENT-ORIENTED PAYING

As mentioned in §4.2.2 Teplast could also introduce another reward system. Right now Teplast is using the time rate. Payment by results would not help, because the quality is supposed to get better and not the quantity. Therefore Teplast could apply performance-related pay; whenever a machine operator works without errors, he gets paid more. If this is applied on an individual basis, Teplast would need to check all products. This is a lot of effort and would include a lot of time. However, this could help to motivate the machine operators. But it could also make other employees jealous.

Otherwise it can be done on a general basis. If the failure rates decrease, every worker will get paid more. But this could perhaps lead to the reverse and demotivate workers, because they end up blaming the person, who is responsible for the most product failures and for this reason also for their lower wages.

Benefit: higher motivation leading to better quality

Drawback: higher payments, requires quality check of all products

6.5 IMPLEMENTING JUST-IN-TIME PRINCIPLES

As described in §4.2.3 Teplast can apply JIT methodologies without actually switching to JIT manufacturing. What could be very helpful for Teplast, is to lower the WIP level. As already mentioned "virtually all the benefits of JIT either are a direct consequence of low WIP levels (e.g., short cycle times) or are spurred by the pressure low WIP levels create (e.g., high quality levels)" (Hopp & Spearman, 2000, p.165). To achieve this the sales department must communicate with the work preparation department, if they should accept more orders or not. Especially when people are on holidays that means that there is less capacity. In order to achieve this, the work preparation department could set limits, which must not be overstepped. For instance the say in March, we do not want to accept more than 500 production orders. But probably it is better solution to make everybody realize that less WIP (less orders) leads to a shorter LT and if the LT is shorter, more jobs can be processed during the year and the customer is more satisfied, because products arrive faster and with a better quality.

Benefit: better quality, shorter LT

Drawback: difficult to implement, if sales department and work preparation department does not work together

6.6 More material in stock

The material analysis showed that there are some troubles with two materials: POM, PE 1000. Teplast can order more of these in advance to fill up the stock, since older material is easier to process (see §5.1.2.3). Therefore it is important for the worker at the saw that he/she takes the material which is in stock for the longest time (first come, first serve principle).

Benefit: less material failures, better quality

Drawback: capital commitment, stock costs

6.7 Conclusions

In conclusion all alternatives can be implemented to improve product quality, but Option 4 is the least promising, because performance-related pay is risky and can also bring demotivating effects. Option 5 is difficult to implement and would rather be applicable on a long term basis. The most promising one is Option 1, because the effort is not that big and it could really help to prevent errors at the source, because by writing measurements down the operator can see immediately, if something is wrong and can fix it right away.

7 CONCLUSIONS AND RECOMMENDATIONS

Finally we are able to answer the last two research questions in this chapter:

- What is the advice concerning the core problem?
- What other problems were seen and how could they be solved or improved?

Concerning the core problem, which is the high amount of product failures, we find that the most common product failure occurs, because of sloppiness during the checking of product and lack of preparation. Also buying the material on short term increases the amount of material failures. We find that most problems occur at the machines and especially at the three machine of type M1, which are suction plates. This number is not surprising, because 44% of all production orders pass one of these M1 machines and therefore it is logical that most products fail at these machines. Besides, new machine operators normally start working at the M1 machines. Quantifying the product failures of M1 machines, gives the product failure rates: p_{S_E}= 0.8% (scrapped M1 production orders returning from customer), p_{S_I}= 1.8% (scrapped M1 production orders detected at quality check), p_{D_E}= 0.8% (defective M1 production orders returning from customer) and p_{D_I}= 6.3% (defective M1 production orders detected at quality check). Consequently there are 90.4% M1 production orders, which are delivered to the customer with a good product quality (p_G= 90.4%). Due to lack of data we cannot compute the amount of product failures that are fixed before they reach the customer or quality check. The results of the impact analysis show that if the product failure rates increased by 20%, the LCT resp. the MLT would be reduced by 7%.

We will recommend alternatives to reach these 20% or maybe more. It is important to say that these are general alternatives, which do not focus the M1 machine and will therefore decrease the general product failure rate at Teplast. Furthermore, we will recommend also other points, which do not concern the core problem of product failures. Considering the core problem, we recommend to implement the following points in the short term (see §6.7).

Integrated quality check at the machine
It is easy to implement and would only cost some extra time and can have a huge impact on the product quality, because workers really have to write their measurements down and therefore it becomes their responsibility to have good measurements and need to fix it right away. Teplast would still have to decide whether it should be applied on a 100% basis or not.

Quality check of all technical drawings
This would need an extra worker therefore the effort is quite big and it would not be appreciated by every workers, so this is a difficult decision, which would be up to Teplast to make.

Remarks for the finishing department
Adding remarks for the finishing department, can solve the problem of deburring too much. It can be easily implemented, and would have a little extra impact.

More material in stock
This option is already requested by the work preparation department. Until now this option was always rejected due to capital commitment. But at least this could be introduced for the blanket orders, which will be produced at some point anyway. It is also important that the material is stored well, because messiness in the storage can also increase material failures.

In the long term the WIP has to become less. To make that happen the communication between the departments has to work. It is really important that sales department knows the limits of the production. As proven by Little's Law, if the WIP will be less, the CT and finally the LT will be less. In the end the same amount of jobs can be done in a year, but in shorter time. The only negative point is that you cannot accept all orders. A lower WIP level has also a positive influence on the product quality.

Furthermore the price and time calculation should be done by the working department without influence of the sales department, otherwise the approximations cannot fit reality. Furthermore we recommend to collect more data to make better decision and better approximations. For instance there is no data of machine failures, even though you cannot always prevent machine failures, it plays an important role in the production. Normally there is also no data about the internal reclamations. Teplast only collected this data for a certain period, which was used for this research. External reclamations are recorded in the systems, but nobody knows them. However, this data should be collected and put into relations with the production orders arriving. For example Teplast could measure the amount of production orders and external and internal reclamations for every month and use it to post the failure rate. On a long term basis Teplast should try to record the data of product failures, which occur occasionally and are being fixed before reaching the quality check or customer. Furthermore there is no precise measurement of process times, which makes it impossible to make proper approximations. There is a stamping system, which cannot precisely show, when an employee started his work and finished it. Another point is that the “Aupos” program is not including a lot of factors (e.g. pauses), therefore the planning cannot be done properly.

If there are at some point no orders for some machines, but there are still blanket orders, which are not needed yet requested by the customer, these blanket orders should be produced. This creates more efficiency. Another point is that the allocation of production orders to the machines should be distributed more evenly. Teplast should not allot all orders to one machine, when there are other machines, which can do the same job.

Moreover, every day the afternoon and night shift overlap. Overlapping of shifts is most of the time a waste of human capital and money. Also when hiring students, there should be more consultation with the particular departments, because also low paid students are a waste of money, if there is no work for them.

The working load at machine 1 is really high (see §5.3.2), so Teplast should maybe think about getting a new machine of type M1. But therefore factor z, which indicates the fraction of production orders that are allotted to M1, should be analyzed again on a long term basis, in order to see how many production orders are really allotted to M1. A z value of 0.35 leads to a traffic load of 75% and 0.40 leads to a traffic load of 85%, both are considered as high traffic, but because the calculations are based on assumptions, we would only recommend this option, when the factor z is higher than 0.40.

BIBLIOGRAPHY

Al Hanbali, A. (2015). *Advanced Production Planning* [PowerPoint slides]. Retrieved from Department of Industrial Engineering and Management, University of Twente Blackboard: https://blackboard.utwente.nl https://blackboard.utwente.nl

Boddy, D. (2011). *Management: An Introduction (5th ed.).* Essex: Pearson Education Limited

Chao, L. P. & Beiter, K. A. (2001). *Design Process Error-Proofing: International Industry Survey.* Paper presented at DETC '01: ASME Design Engineering Technical Conferences. Pittsburg, PA

Chowdhury, S. (2005). *Design for Six Sigma: The Revolutionary Process for Achieving Extraordinary Profits.* Chicago, IL: Dearborn Trade Publishing

Creswell, J. W. (2003). *Research Design - Qualitative, Quantitative, and Mixed Methods Approaches.* Thousand Oaks, CA: SAGE Publications, Inc

Deuermeyer, B. (1994). Interoffice Memorandum on Undergraduate Curriculum in Industrial Engineering. Texas A&M University

Heerkens, H. & van Winden, A. (2012). *Geen Probleem. Een aanpak voor bedrijfskundige vragen en mysteries*. Buren, GLD: Business School Nederland

Hopp, W. J. & Spearman, M. L. (2000). *Factory Physics: Foundations of Manufacturing Management (2nd ed.).* New York, NY: Irwin/McGraw-Hill

Inman, R. R., Blumenfeld, D. E., Huang, N., Li, J., & Li, J. (2013). Survey of Recent Advances on the Interface between Production System Design and Quality. *IIE Transactions, 45*(6), 557-574.

Laugen, B.T., Acur, N., Boer, H. & Frick, J. (2005). Best Manufacturing Practices. What Do the Best-Performing Companies Do? *International Journal of Operations & Production Management, 25*(2), 131-150

Ross, S.M. (2014). *Introduction to Probability Models (11th ed.).* Waltham, MA: Academic Press

Schutten, M. (2014). *Production Planning and Scheduling* [PowerPoint slides]. Retrieved from Department of Industrial Engineering and Management, University of Twente Blackboard: https://blackboard.utwente.nl

Shimbun, N.K. (1988). *Poka-Yoke: Improving Product Quality by Preventing Defects.* Portland, OR: Productiviy Press, a division of Productivity Inc.

Symbol BV. (2014). *Lean Six Sigma Green Belt Training.* University of Twente, Enschede

Winston, W. L. (2004). *Operations Research: Applications and Algorithms.* Belmont, CA: Brooks/Cole

Zijm, W. H. (29. October 2003). *Manufacturing and Logistic Systems Analysis, Planning and Control* [lecture guide]. Department of Industrial Engineering and Management, University of Twente, Enschede

APPENDIX

APPENDIX A - EXAMPLES OF PRODUCTS


Heat resistant milled and turned parts


Gear wheels and chartings


Workpiece carrier


Transportation star wheels


Plastic holder


Shaped screens

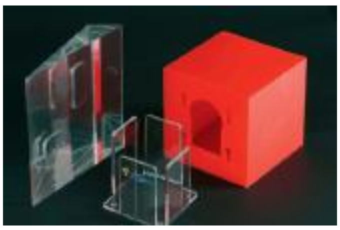

Plastic ducts


Milled profiles


Extruded profiles


Machine protection cover


Vacuum vessel


Displays


Housings

APPENDIX B- 4-EYES-CHECK

Teplast Herbert Terbrack GmbH & Co. KG | Gutenbergstr. 1 | 48683 Ahaus | Tel: 02561/9825-0 | Fax: 02561/9825-25 | www.teplast.de

4-Augen-Kontrolle teplast

Fert.-Auftr.-Nr.:	
Auftrag-Nr.:	
Position:	
Afo:	

AV-Bearbeiter: ______________________

Intervall entsprechend der AFO - Beschreibung entnehmen!

Datum	bei Stückzahl	Unterschrift Prüfer 1	Unterschrift Prüfer 2

Mit der Unterschrift wird bestätigt, dass die 4-Augen-Kontrolle durchgeführt wurde und die Maße korrekt waren!

Figure 13: This figure shows the 4-eyes-check document, Teplast is currently using.

APPENDIX C – TABLE 5 & 6

no.	pieces	material	
Internal reclamations			
5	1	PET GVO grey	
7	**200**	PE 500	no 4-eyes-check
39	8	POM black	
41	3	PET GVO grey	
78	6	POM black	
80	12	PA 6 C natural	
100	8	POM natural	
102	1	PE 1000	
120	1	PEEK natural	
122	1	PE 1000	
135	1	PA 6 G	
137	1	PET black	
150	1	POM black	
152	10	PEEK red	
180	1	POM black	
182	1	PET black	

204	10	POM natural	
206	10	POM natural	
239	**120**	POM black	no 4-eyes-check
241	1	PE 1000 natural	
260	20	POM natural	
262	1	PET black	
287	35	PE 500	
289	35	PE 500	
306	1	PE 1000	
308	1	POM black	
322	1	PE 1000	
324	1	PE 1000	
340	1	PET natural	
342	1	PE 1000	
67	1	PETP natural	
69	1	PE 1000	
109	**200**	POM natural	no 4-eyes-check
111	1	PE 1000	
154	1	PE 1000	
156	3	PTFE	
186	6	POM black	
188	1	PET black	
201	**150**	Lauramid natural	4-eyes-check
203	30	POM natural	
233	3	POM natural	
235	4	PA 6 C natural	
250	1	PEEK natur	
252	32	PET grey	
280	2	PE 1000	
282	14	PET black	
300	2	POM PE blue	
302	1	PEEK FG	
315	3	POM natural	
317	2	PEEK natural	

Table 5: This table shows a failure analysis of internal reclamations regarding the piece number and material.

no.	pieces	material
External reclamations		
1	1	PA 6 G
2	1	PE 1000
3	1	PE 1000
4	1	PET black
5	1	PE 1000
6	29	PET natural
7	1	PE 1000
8	8	POM black
9	8	POM black
10	16	PE 1000
11	2	PE 1000
12	4	POM natural
13	1	POM black
14	10	PET GVO
15	9	PET GVO
16	4	PE 6 C
17	8	PA 6 G
18	1	PE 1000
19	1	PA 6 C
20	479	PA 6 C
21	2	PETP natural
22	17	POM natural
23	?	?
24	1	PA 6 C
25	44	PP
26	2	PE 1000
27	2	PE 1000
28	1	POM natural
29	91	PA 6 C
30	1	PA 6 C
31	5	PEEK
32	32	PE 1000
33	32	PEEK
34	36	POM black
35	1	PA 6 C
36	1	PP
37	9	PTFE
38	1	PA G 6
39	2	PA 6 C
40	23	POM black
41	22	POM natural
42	?	?
43	5	PET black

44	204	PMMA
45	19	PMMA
46	29	POM black
47	5	PEEK
48	1	PEEK
49	1	PET natural
50	10	PETP TX
51	520	PA 6 G
52	1	PET natural
53	4	PE 500
54	1	PE 500
55	2	POM natural
56	87	PA 6 G
57	40	POM natural
58	5	PEEK
59	4	PE 1000
60	1	PTFE
61	45	PETP natural
62	5	PE 500
63	17	POM natural
64	6	PEEK
65	1	PET natural
66	24	PEEK
67	1	PE 1000
68	3	POM natural
69	1	PE 1000
70	4	PA 6 C
71	1	PE 500

Table 6: This table shows a failure analysis of external reclamations regarding the piece number and material.

APPENDIX D - COMPUTING C_{ai}^2 FOR NEW PRODUCT FAILURE RATES

Reduction of the failure rate	**20%**	**40%**	**60%**	**80%**	**100%**
i	C_{ai}^2				
1	0.66	0.66	0.66	0.66	0.65
3	0.99	0.99	0.99	0.99	0.99
4	0.99	0.99	0.99	0.99	0.99
5*	0.65	0.65	0.65	0.65	0.65
9	0.86	0.86	0.86	0.86	0.86
10	1.10	1.10	1.10	1.09	1.09
11*	1.02	1.01	1.01	1	0.99
13*	1.15	1.15	1.15	1.15	1.15
14*	1.28	1.29	1.3	1.31	1.33
15	0.97	0.99	1.01	1.02	1.03

Table 7: This table shows the SCV of interarrival rates at each working stations for the new product failure rates.