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# TWENTSCHE KABELFABRIEK BV

Reducing process variation on the Coating line at TKF by implementing a statistical analysis method

UNIVERSITY OF TWENTE.

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# Preface

Dear Reader,

In front of you lies my report for the bachelor's thesis that is about implementing a statistical analysis method on the Coating lines at the Twentsche Kabelfabriek. This thesis is written for the Bachelor of Industrial Engineering and Management at the University of Twente. The research has been conducted at the Twentsche Kabelfabriek (TKF) in Haaksbergen, the Netherlands, from February 2022 until June 2022. This thesis performs research on the implementation of a statistical analysis procedure in order to reduce the process variation on the Coating lines at TKF.

I would like to thank all the operators and managers of the Twentsche Kabelfabriek who were always open to helping me with the research and answering questions about the production process of fibre optics cable. It was a really interesting experience to be part of this team. A special thanks to my company supervisor A. ten Tije for his support during the project and his lessons about statistics and process control.

Furthermore, I would like to thank my first and second supervisors from the University of Twente, Matteo Brunetti, and Marco Schutten, for all their time and useful feedback throughout the project. Their feedback helped me a lot to improve the quality of the research.

Enjoy reading this thesis.

Jorn de Ruiter

August 2022

# Management summary

The Twentsche Kabelfabriek (TKF) is a cable manufacturer in the Netherlands for the worldwide market. The purpose of this research is to investigate whether it is possible to implement a statistical analysis method on the Coating line at TKF in order to reduce the process variation, optimize process control, and improve the production process of fibre optics cable.

**Problem context**

The core problem of TKF is the current analysis method on the attenuation value of fibre optics cable of the coating process. At the Coating line, the transparent fibres are bundled and provided with a tube. This tube is meant as an identification and protection layer. After the production at the Coating line, the tube is measured to determine the attenuation value of the fibres. The attenuation of fibre optics can be identified as the reduction of power when data is transmitted through the fibre. However, in the current situation, the company uses a go, no-go system which means that the fibres are checked on whether this value meets the specification standards of the company. In this situation, it is not possible to detect patterns between consecutive batches and find process variations. The implementation of a statistical analysis method enables monitoring the process variation by constantly controlling the process and helps to improve the performance of the production process. To tackle this problem, we define the following main research question:

*'How can a statistical analysis method contribute to and be implemented into the Coating line at TKF?'*

**Statistical evaluation**

In order to implement a statistical analysis method, we first analyse the current performance of the Coating line. Therefore, we start by investigating whether the measurement system is reliable and valid. However, the Measurement System Analysis in this research has demonstrated that one of the two measurement systems does not meet the acceptance standards. This means that the data that comes from this measurement system is not reliable. Furthermore, the research on the number of incorrect measurements shows that nearly 20% of the total measurement demonstrates errors due to human operators. So, the current performance of the coating process is hidden by inaccuracies in the measurement procedure. Nevertheless, the analyses regarding the coating process have determined that the Coating lines at TKF approach a Six Sigma process. A Six Sigma process means that the process is able to produce less than 3.4 parts per million (ppm) outside the specifications prescribe. This index is better known as the number of defects. In Section 3.3, we describe more about a Six Sigma process.

**Improvements regarding the measurement**

To improve the measurement procedure, we established several points for improvement. First of all, the training of the operators. Since we observed many failures concerning the measurement caused by operators, we recommend including the measurement procedure in the training program for the operators at TKF. Adding this to the training program saves a significant amount of time, stress, and measurement errors. Furthermore, we discovered that the workplace is unorganized, and equipment is often lost. Therefore, the measurement procedure for operators is inefficient since they first have to clean the workplace and find the right tools. To improve this situation, the company should introduce the 5S method. 5S helps to structure the workplace. Finally, we advise the company to conduct a new Measurement System Analysis, with well-trained operators, a clean workspace, and batches from a wider spectrum. This way, the company should try to prove the reliability and validity of the measurement system.

**Implementation of a statistical analysis method & Dashboard**

The implementation of a statistical analysis method helps to detect process patterns and reduce process variation. Furthermore, the studies regarding the performance of the coating lines have shown a lot of Out-of-Control situations when the control limits are considered. When the attenuation value of a fibre lies between the control limits, the system is In-Control. Otherwise, we speak of an Out-of-Control (OoC) situation. In this case, there is probably an error in the system. Since there are many of these OoCs, we recommend implementing SPC on the Coating lines at TKF. For the dashboard of TKF, we decided to use the Xbar- and R-charts. These control charts provide information at fibre level that makes a better analysis of the process variation of the Coating line possible. Together, with the control limits in the charts, we determine whether the process is In- or Out-of-Control.

# Table of Contents

## List of Abbreviations

| Abbreviation: | Definition: |
|---|---|
| *FTR* | First Time Right |
| *KPI* | Key performance indicator |
| *KPIV* | Key Process input variable |
| *KPOV* | Key Process output variable |
| *LCL* | Lower control limit |
| *LSL* | Lower specification limit |
| *MSA* | Measurement System Analysis |
| *OCAP* | Out-of-Control Action Plan |
| *OoC* | Out-of-Control |
| *R&R* | Repeatability & Reproducibility |
| *SPC* | Statistical Process Control |
| *TKF* | Twentsche Kabelfabriek |
| *TKH* | Twentsche Kabel Holding |
| *UCL* | Upper control limit |
| *USL* | Upper specification limit |

# 1. Introduction

For this thesis, we have conducted research on the production process of fibre optics cable at the Telecom department of the Twentsche Kabelfabriek (TKF) in Haaksbergen, the Netherlands. This graduation thesis is about the attenuation value of the fibre optics on the Coating lines 'SeC 6' and 'SeC 9'. Currently, there is Statistical Process Control (SPC) software running in the first part of the production process. This SPC-software statistically monitors and controls the production process of fibre optics at the Colour line.

This research is a follow-up study that has been done by a student from the Saxion University of Applied Sciences Enschede (Kost, 2021) and a student from the Hanze University of Applied Sciences Groningen (Slomp, 2021). These students have completed Phase-1 and Phase-2 of the implementation of a statistical analysis method on the production process of fibre optics cable. The main focus of Phase-1 was to orientate for a suitable analysis method in order to monitor the process variation between consecutive batches on the Colour line. During Phase-2, the focus was on the implementation of this analysis method at TKF by creating the software. At the Colour line, the transparent fibres are provided with a thin colour layer that serves as a protection and identification layer.

Now we arrived in Phase-3. In this phase, we investigate whether SPC is also suitable for the Coating line. The company desires to investigate whether it is possible to implement this statistical analysis method also on the Coating lines at TKF. The coating process is the second step of the production process of the fibre optics cable. Chapter 2 explains the production process of fibre optics cable in-depth. This chapter continues with a short introduction to the Twentsche Kabelfabriek (TKF) in Section 1.1. Here, we explain the history and goals of the company. In Section 1.2, we indicate the problem, and in Section 1.3, we define the research questions and provide an overview of the thesis structure. Section 1.4 elaborates on the research methods. Finally in Section 1.5, we define the research scope.

## 1.1 History & Goals TKF

*Figure 1: The factory of TKF in the early years*

The Twentsche Kabelfabriek was founded in 1930 by Johannes Cornelis van der Lof. Already in the early years of the 20th century, he had his own cable installation and fitting company. With the experience gained during his years as mechanic, he established together with Jan Derk Odink the NV Twentsche Kabelfabriek in Haaksbergen (A. Tije, 2022). Figure 1 shows a picture of the production location of TKF in the earlier years. In the first years, the main focus of TKF was on the expansion of the company in the Netherlands and neighbour countries. In 1953, the company became quoted on the Amsterdam Stock Exchange. The main reason to be a listed company, was to facilitate the expansion of the company worldwide. After some years of large expansions of the company, NV TKF decided to create N.V. Twentsche Kabel Holding (TKH) in 1980. Due to the acquisitions of several companies in the Netherlands and in Germany, it was necessary to establish the holding TKH (A. Tije, 2022).

Currently, the four core segments of TKH are Vision & Security, Connectivity, Manufacturing, and Communications systems. Vision & Security focuses on improving and controlling the quality of an operation by using 2D and 3D cameras. This way, customers are able to manage and monitor for instance logistics or production processes. Furthermore, these technologies improve sustainability and safety in numerous markets, e.g., infrastructure or building security. The Connectivity segment focuses on integrating hardware systems with intelligent software by using smart technologies. The key element of Manufacturing is automating production processes in different industries, e.g., tire production for cars or the distribution of medicines (A. Tije, 2022). Finally, the Communication technology. This technology focuses on the transition of data and is the main technology of this thesis.

In order to stimulate the growth and profitability of the company, the strategic program 'Accelerate 2025' has been introduced. This program should achieve an acceleration of organic growth combined with more profitability and a higher growth potential (A. Tije, 2022). In the mid-term and long-term, TKH will focus on three different tracks. First the environmental perspective, the goal of TKH is to be 100% CO2 neutral by 2030, which means that TKH will reduce its harmful emissions as much as possible and offset the rest. Besides, TKH aims to make at least 80% of the materials recyclable and reduce the production waste to less than 5%. From a social perspective, important issues are women's emancipation, a low illness rate and employee satisfaction of at least 7.5 on a 10-point scale. Finally, from a governance perspective, the main purpose is to enhance the sustainability policies and procedures (A. Tije, 2022).

## 1.2 Problem identification

As mentioned at the start of this chapter, we focus on the second step of the production process of fibre optics cable. A fibre optics cable consists of multiple fibres and protection layers and has several characteristics. One of these characteristics is the attenuation value of the fibres. The attenuation can be identified as the reduction of power when data is transmitted through the fibre. For a more detailed explanation of attenuation, we refer to Section 2.1. The attenuation value of the fibre optics is measured by an optical time-domain reflectometer (OTDR) system. After every step in the production process, the operators measure the fibres. At the Colour line, only one fibre has to be measured which takes only a few minutes. For the Coating line, it takes a bit longer, around 5 to 15 minutes, because a tube consists of multiple fibres. However, the time it takes for the measurement procedure is almost negligible with respect to the complete production process since the fibres can be measured simultaneously as when the machine is running. So, the changeover time of the process is only marginal affected by the measurement procedure.

In the current situation, the analysis of the retrieved data is not as accurate as desired by the company. The company uses a go, no-go system to check whether the attenuation complies with the specification limits defined by the research and development department of TKF. However, the fibre optics reels are not tested on statistical relationships, e.g., on the variability between consecutive batches. This way, it is impossible to detect any pattern between the reels and understand the process variation of the production process. For example, why a production line is constantly producing above or below average. This could lead to late interventions when a defect occurs. Therefore, the company would like to introduce a statistical analysis method on the production lines that monitors and control the production process in real-time. For implementing a statistical analysis method, we have to calculate the control limits for the process. The control limits are not equal to the specification limits. The specification limits represent the wishes of the customer, whereas the control limits enable the company to determine whether the process is In- or Out-of-Control. Therefore, the specification limits of a company could be larger than the control limits. When the attenuation value of a fibre lies between the control limits, the system is In-Control. Otherwise, the system is Out-of-Control. Then, a manager has to inspect the production line. Section 3.3 provides more information about control limits.

To get a better understanding of the core problem of this thesis, we set up a problem cluster. A problem cluster shows all the correlated causes of a problem and should be followed back to the problems which have no direct cause themselves in order to find the core problem (Heerkens & van Winden, 2017). If we apply this approach to the problem cluster for this research, the cluster indicates four different core problems, as displayed in Figure 2. In this research, we focus on three core problems. We discuss the first two problems together: the "inaccurate measurement system" and the "inaccurate measurement by human errors". The main core problem for this research is the third core problem and can be defined as "Limits of the attenuation value fibre optics (FO) are defined by standard specifications".

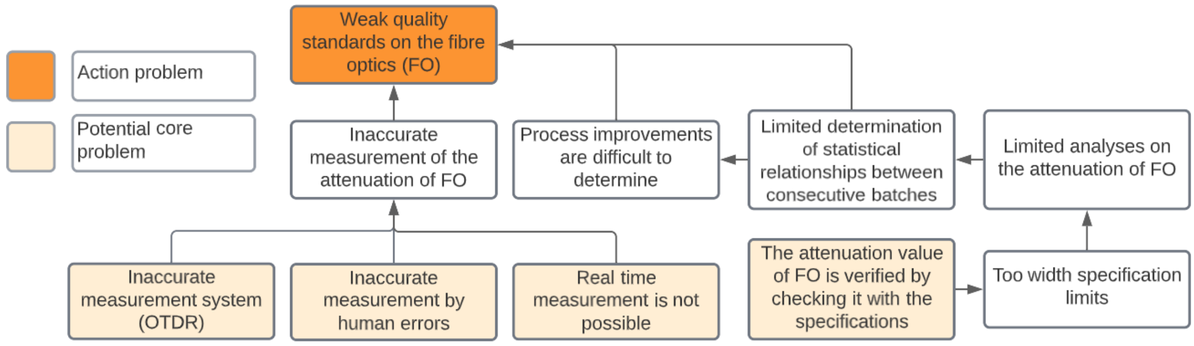


*Figure 2: Problem cluster coating line Twentsche Kabelfabriek*

In order to understand how the statistical analysis procedure contributes to improving the attenuation value of the fibre optics, we focus on the following main research question:

*'How can a statistical analysis method contribute to and be implemented into the Coating line at TKF?'*

The purpose of the statistical analysis method is to identify process variation in order to detect relationships and make improvements to the production process of the cable. To be able to monitor and control the fibre optics cable process, the company wants to implement a statistical analysis method. The aim of TKF is to implement this procedure after every production step. This means that we plan to use the analysis method three times during the production process: At the Colour line, Coating line, and Mantle line. These production lines are described in-depth in Section 2.1. T Although a quality test after every production step seems like a time-consuming activity, it is essential since it is very costly to disapprove a cable because of one single fibre. For instance, when an operator produces a tube with twelve fibres and one of these fibres has a too high attenuation value. If the operator does not observe this failure after the production on the Coating line, the failure will be noticed at the final inspection. Then, the complete fibre optics cable has to be disapproved. Otherwise, only one tube was disapproved.

## 1.3 Research questions

As mentioned in Section 1.2, the operators of TKF are analysing the attenuation value only on whether the amplitude value complies with the standard specifications defined by the research and development department of TKF. However, using this way of analysing provides only limited insight into the process variation. For this reason, the company wants to implement a statistical analysis method, which helps increase the knowledge about the Coating line and narrow the width of the process variation. Furthermore, implementing this procedure contributes to detecting sooner Out-of-

Control situations and provides more knowledge on how to prevent them. When an Out-of-Control situation occurs, the batch is placed in quarantine. Then, a manager has to inspect the reel for deviations. If this person does not see major issues, the reel can be used for the next production step. Otherwise, the manager has to disapprove of the reel. However, this inspection is very time-consuming since the complete reel has to be checked. So, for this reason, the company wants to avoid quarantines.

In order to improve the current situation and answer the main research question defined in Section 1.2, we set up several research questions (RQ). These research questions help to obtain the necessary information about the problem and to formulate a final conclusion (Heerkens & van Winden, 2017). We link the questions below to the different chapters of this report.

**RQ1:** What does the production process look like?

1. What are the production steps of the fibre optics cable?
2. How are the optical fibres currently being measured and analysed?

For research question 1, we map the coating process and explain the measurement procedure of the fibres.

**RQ2:** What is the theoretical background behind the different theories used in this research?

1. Which method is a suitable research method to reduce process variation and improve the process performance of a production process?
2. What is an appropriate analysis method to monitor the production process?
3. What are suitable studies to measure the current performance of the production process?
4. How could we indicate whether a variable influence the production process?

For research question 2, we investigate why we use certain methods and theories to investigate the performance of the process and how to implement a statistical analysis method.

**RQ3:** What is the baseline performance of the coating process?

1. How does the measurement system perform?
2. What are the statistical characteristics of the fibres?

The main focus of research question 3 is to determine the performance of the measurement procedure and identify the statistical characteristics of the data. For this research question, we determine the variance and the mean. Furthermore, we execute a measurement analysis to prove the reliability and validity of the measurement system. Finally, we discuss the distribution that fits best to the data.

**RQ4:** To which extent is it possible to standardize the control limits for different types of tubes and Coating lines?

1. What is the current performance of the Coating line?
2. To which extent have the different types of fibres an impact on the attenuation value?
3. To which extent have the different Coating lines an impact on the attenuation value?

By using statistical analysis procedures on the Coating line, the purpose is to detect errors at an earlier stage. To implement this procedure, the first step is to measure the current process performance of the Coating line. Then, we examine whether the different types of tubes and Coating lines have an impact on the attenuation value. After this has been completed, we are able to analyse the system and find causes that could decrease the process variation.

**RQ5:** Which implementations improve the process performance on the Coating line?

1. What are possible improvements regarding the measurement of attenuation of the fibres?
2. What is the potential process performance on the Coating line?
3. Which software improvements are required for the implementation of SPC?

For research question 5, the possible improvements to the coating process are determined regarding the measurement. Besides, for this research question, we determine the potential process performance and compare this performance with the process performance studies from Chapter 4. Finally, the requirements for the SPC software are established.

**RQ6:** How will the improvements be sustained after the project closure?

1. How should the improvements be measured and controlled on the Coating line?

For the final research question, the focus is on how to sustain the statistical analysis method after the project closure. Therefore, we provide a plan of action for the operators and managers about how they should use this approach in the future. Finally, the right improvements should be measured and controlled to be able to check and control the performance of the process.

To implement the statistical analysis method on the Coating line at TKF, we use the research cycle of the Lean Six Sigma (LSS) theory. The LSS theory is a proper method to improve a production process. This method consists of five stages: Define, Measure, Analyse, Improve and Control (DMAIC). In Section 3.1.1, we explain the research method in more detail. Each of the research questions is linked to a stage of the DMAIC research cycle. The thesis is structured as follows. In Chapter 2, we start by explaining the production process of fibre optics cable. This chapter is linked to the Define phase of the DMAIC method. Chapter 3 provides the theoretical background behind the different theories used in this thesis. In Chapter 4, we perform a statistical evaluation of the measurement systems and the production process, which corresponds to the Measure and Analyse phases of the DMAIC cycle. Chapter 5 provides the measurement improvements, the potential performance of the production process, and it explains how to sustain the improvements after project closure. This chapter is related to the Improve and Control phase. Table 1 shows a structured overview of the different stages related to the research questions and chapters of this thesis. Besides, the table exhibits an overview of the thesis build-up. Finally, in the last column, we explain which type of results we acquire for each of the chapters.

*Table 1: Thesis build up*

| Chapter: | Stage | Research question | Results |
|---|---|---|---|
| 2 - Production process of fibre optics cable | Define | RQ 1 | A detailed explanation of the production process. |
| 3 - Literature study | - | RQ 2 | The purpose of this chapter is to get more insight into the key concepts of the thesis. |
| 4 - Statistical evaluation of production process | Measure | RQ 3 | Determination of the reliability and validity of the measurement system. Besides, a calculation of the statistical characteristics of the tubes. |

| | | | |
|---|---|---|---|
| | Analyse | RQ 4 | Insight into the current capability and performance of the process. Furthermore, an insight in the degree of influence of the different Coating lines and fibres. |
| 5 - Improving the production process | Improve | RQ 5 | We provide the potential process performance of the Coating line and an explanation of the importance of statistical analysis. Furthermore, we provide a draft version for the dashboard of the software. |
| | Control | RQ 6 | We explain how to maintain the process improvements. |

## 1.4 Research scope

The goal of this research is to improve the production process by implementing a statistical analysis procedure. This procedure will help to reduce process variation, continuously monitoring of the process and supports decision making. The statistical analyses are appropriate to determine improvements and execute these in the coating process. In this way, the purpose is to improve the process performance. The research focuses on the Coating line at the cable manufacturer TKF. The coating process is the second step of the production process of fibre optic cable, as described in Section 2.1. The production steps before and after the Coating line are excluded from this research. Furthermore, there are four different Coating lines at the production location of TKF in Haaksbergen. However, this research is focussing on the 'SeC 6' and 'SeC 9' Coating lines.

During the research, we use data over the period of weeks 1-20 from 2022. These datasets originated from the Coating lines 'SeC 6' and 'SeC 9'. The 'SeC 6' can be seen as the older brother of the 'SeC 9'. The datasets contain information about the type of tube, fibre, production number, reel number, and attenuation value. Appendix A.1 exhibits an example of a dataset used for the research. Every row consists of data of one fibre this means that a tube of twelve fibres is equal to twelve rows of data. A tube can be recognized by the same production number. Furthermore, we distinguish at which production line and measurement station the reel has been produced and measured. For this research, we use approximately 100,000 entries of data.

# 2. Production process of fibre optics cables

In this chapter, we discuss the coating process. First, in Section 2.1, we start with a schematic overview of the production process of fibre optics cable. Then in Section 2.2, we describe the coating process in more detail. Finally, in Section 2.3, we go more in-depth into the measurement of the fibres within the tube. The central research question in this chapter is identified by RQ1:

"What does the production process look like?"

We divide this problem into the following sub-questions:

- "What are the production steps of the fibre optics cable?"
- "How are the optical fibres currently being measured and analysed?"

## 2.1 Production process fibre optics cable

The telecom department of the TKF produces fibre optic cables for the worldwide market. The production process of these cables starts in China. Through thermal fibre drawing, the fibre optics are extended into lengths from a macro-structured preform to a micro-structured transparent fibre. After this has been completed, the fibre optics are shipped to the production location in the Netherlands. In this production location, the transparent fibres are transformed into fibre optic cables. The production process in the Netherlands consists mainly of five different steps, as displayed in Figure 3. At the time the transparent fibres arrive at the location in Haaksbergen, the fibres get first a thin colour layer at the Colour line. Then, the fibres move forward to the Coating line. At this line, the fibres are bundled together and provided with a tube layer. Next, the bundles of fibres are combined with other bundles and provided with the inner sheath. Finally, the fibre optics cable gets some extra protection sheaths and will be inspected for final approval. Furthermore, during every step in the production process, the fibre optics are controlled and inspected for deviated characteristics on, for instance, the attenuation value, diameter, or other irregularities.

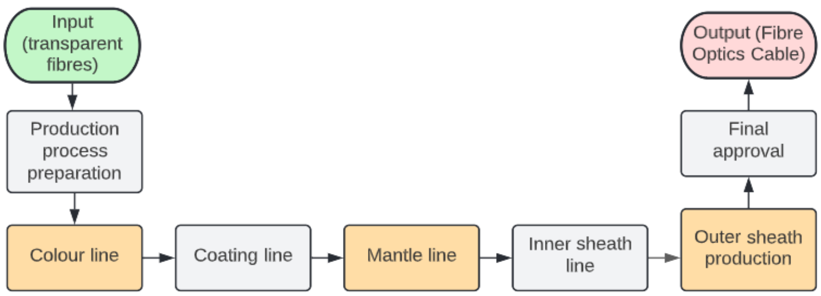



*Figure 3: Production process fibre optics cable*

The fibre optic cable consists of multiple fibres and different protection layers. At the TKF, several kinds of fibre optic cables are produced, which can differ in many ways. Table 2 shows the fibres that are investigated during the research: the 234 µm wide V28- and V29-Fibres and the 190 µm wide V30-Fibre. These fibres differ in diameter and quality, whereas the A2-fibre has better quality compared with the A1-fibre. To get a better insight into how the fibre optic cables are built up, Figure 4 shows a cross-section overview of the cable. Next to the difference in diameter and quality, the thickness and strength of the tube could vary. Furthermore, we distinguish two types of tubes: the Loose tube and the Soft Tube. The Loose Tube provides better protection towards the fibres since this tube is a stronger protective layer than the Soft Tube. This research focuses on the Coating line 'SeC 6' and 'SeC 9'. These lines use only the Soft Tubes for production.

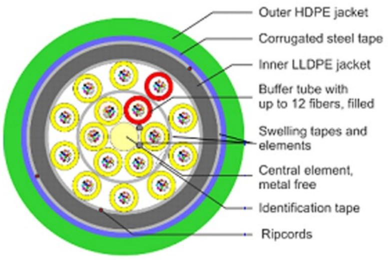





*Figure 4: A cross-section view of a fiber optic cable*

*Table 2: Type of fibres used at the SeC 6 coating line*

| Type of fibre: | Diameter: | Quality: |
|---|---|---|
| *V28* | 234 µm | A1 |
| *V29* | 234 µm | A2 |
| *V30* | 190 µm | A2 |

Another characteristic of fibre optics cable is attenuation. Attenuation occurs at every transmission of a light signal through fibre optics. In fact, when the signal moves through a fibre, there is always a reduction of power, also called attenuation. The attenuation is measured in dB/km and is caused by, for example, the resistance in the cables, cables splices or connectors. In total, four types of attenuation can occur if the signal is disturbed. These types of attenuation are absorption, scattering, micro-bending, and macro-bending (Juniper, 2022). Table 3 defines these types of attenuation.

*Table 3: Causes for disturbing signals*

| Type: | Definition: |
|---|---|
| *Absorption* | This phenomenon occurs when the signal is absorbed by impurities in the fibre and is converted into heat (FOA, 2019). |
| *Scattering* | Scattering happens when the signal collides with individual atoms in the fibre glasses. In this situation, the light is scattered at angles outside the core of the fibre (FOA, 2019) |
| *Micro-bending* | Occurs when pressure is applied to the surface and makes the surface irregular (Twentsche Kabelfabriek, 2016). |
| *Macro-bending* | Macro-bending happens when the fibres are bent into a visible curvature. (Twentsche Kabelfabriek, 2016). |

## 2.2 Coating process

This section describes the process steps of the Coating line at TKF in more detail. Table 4 shows a SIPOC table. Here, we define the production steps of the Coating line from supplier to customer. A SIPOC stands for: Supplier, Input, Process, Output, Customer and helps to determine which phase of the process needs analysis and improvement (Theisens, 2018). In the first column, we find the suppliers for the inputs of the coating process. Then, the second column provides the input materials and the Machine Set-up Document (MIK). This document has all the information about the production, e.g., settings, speed, volume, colour, etc. Next to this, we have the specifications of these materials, to ensure that the operators use the right materials, and the type of input, where S stands for Standard Operating Procedure, and C stands for controllable which means that this specification can be checked on the MIK. The third column describes the process from start to finish. These process steps are thoroughly described in the next section. The Output column shows the end products of the Coating line, and the final column explains the customer of the Coating line.

*Table 4: SIPOC analysis*

| Supplier | Input | | | Process | Output | | Customer |
|---|---|---|---|---|---|---|---|
| | | *Specs* | *Type* | | | *Specs* | |
| -Colour line<br>-Begra Granulate GmbH & Co. KG<br>-KBA-Metronic GmbH<br>-MWO GmbH | -MIK<br><br>-Fibres<br>-Ink<br>-Oil/Jelly<br>-Granulate<br>-Master-batch | -Put into computer<br>-MIK<br>-MIK<br>-MIK<br>-MIK<br>-MIK | S<br><br>C<br>C<br>C<br>C<br>C | Start<br>Process<br>Finish | -Reel with different fibres provided with a Tube. | -Control values<br>-Attenuation <0.224dB/ km 1550nm | -Mantle line |


The coating process starts with the preparations of the Coating line. First, the operators have to switch on the main switch of the system. Then, they must open the water and air supply, and finally, they turn on the computer. The operators can find the recipe for the tube in CableBuilder. This is the cable design software of TKF, which has been used at every production line, from standard power cables to fibre optic cables. The software enables to easily manage the production of the cable. In fact, CableBuilder provides all the necessary information about the construction of the cable. From the initial design concept to delivering the full bill-of-material. Moreover, it takes the milestones of the cable, Quotation, Manufacturing Simulation, Quality Assurance, ERP integration and Reporting datasheets into account (Twentsche Kabelfabriek, 2016).

For the production of the tube, the company uses an extruder. This element consists of multiple components. First, the operator fills the hopper with granulate and mixes it with Masterbatches. The Masterbatches provide the colour to the tube and can be compared with small bricks. After the mixture is cooled down, it goes through the worm. Here, there are heating elements and fans in order to get the right temperature. Finally, we find the flange and the neck of the extruder before the fibres will be surrounded by a tube. Important for the production is to configure the requested settings to the system. Therefore, the operators must take the correct nozzle, thorn, worm, and needle to the extruder's head. Figure 5 shows a schematic drawing of how all these elements are connected together. Furthermore, the operators must place the right reels of coloured fibres on the unwinders. All these components can be found in the MIK.

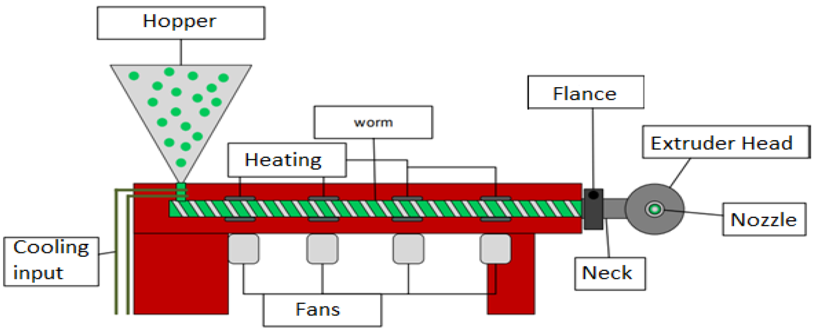



*Figure 5: A schematic drawing of the colour mixer*

When the operators have installed the correct settings on the machine, they are ready to start the production process. Figure 6 provides a schematic drawing of the Coating line at TKF. The figure shows that the process starts at the Unwinding unit. From there, the fibres go through the Extruder and will be cooled down by the Cooling units. After this, the tube goes through the Dual Wheel Capstan to regulate the tension. Finally, the tube goes through the final Capstan before winding around a new reel to be ready for production at the Mantle line.

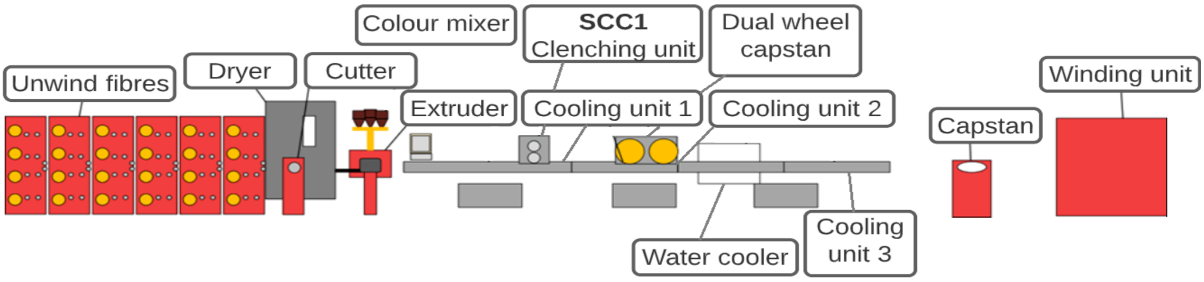



*Figure 6: A schematic drawing of the Coating line*

## 2.3 Measurement procedure

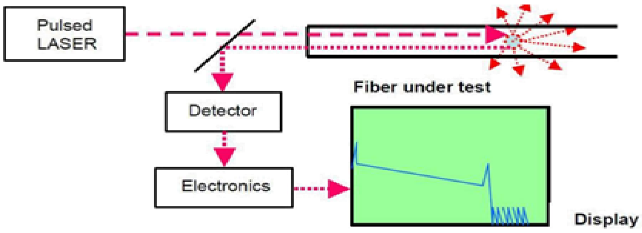


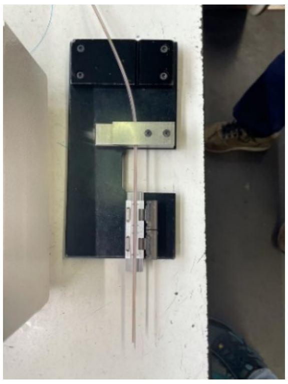

*Figure 7: A schematic overview of the OTDR measurement*

After the production of the reel is complete, the operators inspect the reel to see whether it complies with the specifications. For this inspection, the operators of TKF are measuring the attenuation values of the fibre optics by using an Optimal Time-Domain Reflector (OTDR). This measurement system computes the amplitude values of the fibre optics. As displayed in Figure 7, the reel with fibre optics is connected to a coupler, which is connected to the OTDR. When the operators have connected the fibres correctly, the attenuation value can be measured. The laser of the OTDR emits a pulse of light at a specific wavelength through the fibre. This pulse is either reflected, refracted, or scattered back down the fibre to the OTDR system. The signals will be intercepted and converted into a graphical plot. By checking the graph on the specification limits, the operator can detect Out-of-Control situations (Theisens, 2018).

Before the operators are able to measure the fibres with the OTDR measurement system, they must prepare the fibres. The operators can decide to choose either the manual MAS measurement or the MiniMAS. By using the manual MAS, the operators have to measure every single fibre on its own. Using the MiniMAS, they can place all the fibres simultaneously in the system. Then, the MiniMAS goes automatically through every fibre. For this reason, the MiniMAS should take less time than the manual MAS.

The measurement procedure consists of seven different steps. In Figure 8, we provide all the steps for the inspection of the tube by using the manual Mas & MiniMAS. In the first step, the operators should place the reel nearby the measurement system. Then, in Step 2, they have to place the fibres in the correct order. Third, the operators have to remove the tube and colour layer. In Step 4, the operators cut the fibres into the same length. During Step 5, it is essential that the measurement system is clean in order to place to fibres in the correct position (5a exhibits the MiniMAS and 5b the manual MAS). Next to this, a good connection between the connector and fibres is required to get a valid and reliable measurement. When the operators complete this step, they start with the measurement in Step 6. Here, they measure the fibres on the length and attenuation by using the OTDR. After the operators have completed the measurement, they are able to analyse the attenuation graph, shown in Step 7. If every prompted box is green, the operator places the reel at the designated location. However, when there are still some red boxes, the operator should try a second measurement. If the boxes are red again, the operator has to follow the Out-of-Control Action Plan (OCAP) established for the Telecom department of TKF. This document contains all the information on what to do in case of an Out-of-Control situation.

*Step 1*

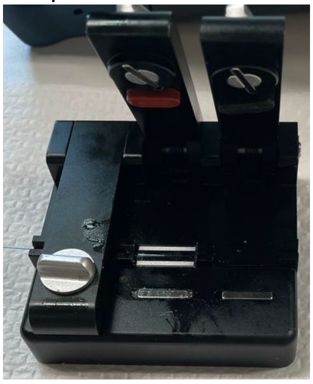


*Step 2*

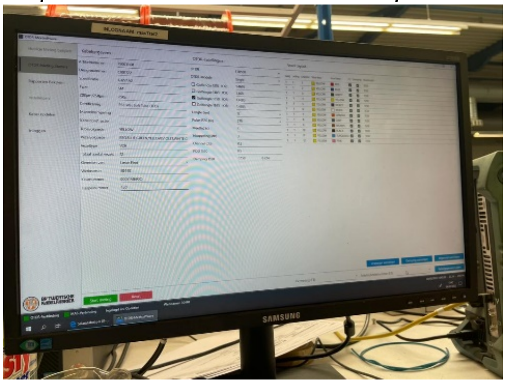
*Step 3*

*Step 4*

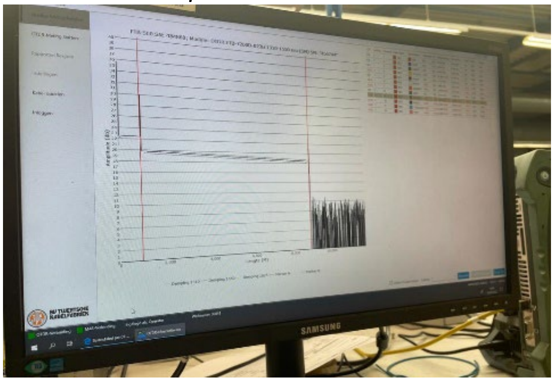
*Step 5a*



*Step 5b*



*Step 6*



*Step 7*

*Figure 8: Steps for the measurement of the transparent fibres*

Finally, Table 5 provides the specification limits of the attenuation for all the fibre types during this research, which are the V29-, V28-, and V30-Fibre. These are the standard specification limits defined by the research and development department. The fibres are checked on whether the attenuation value lies within the specification limits. Here, we have the Lower Specification Limit (LSL) and the Upper Specification Limit (USL) for the measurement at a wavelength of 1310 nm and 1550 nm.

*Table 5: The attenuation specifications used for this study*

| 1310 nm | | 1550 nm | |
|---|---|---|---|
| LSL (dB/km) | USL (dB/km) | LSL (dB/km) | USL (dB/km) |
| 0.300 | 0.374 | 0.150 | 0.224 |

# 3. Literature review

This chapter discusses the theoretical background behind the theories used in this research. Here, we elaborate on the following research question identified by RQ2:

RQ2: "What is the theoretical background behind the different theories used in this research?"

We divide this problem into the following sub-questions:

- "Which method is a suitable research method to reduce process variation and improve the process performance of a production process?"
- "What is an appropriate analysis method to monitor the production process?"
- "What are suitable studies to measure the current performance of the production process?"
- "How could we indicate whether a variable influence the production process?"

After we introduce the problem in Chapter 1 and describe the production process in Chapter 2, we explain the literature behind the research in this chapter. This literature review elaborates on several theories to get a better understanding of the theoretical background of the research. The chapter starts in Section 3.1 by explaining the research methods that are optional to use during this research. Then, Section 3.2 discusses the capability studies. Section 3.3 the statistical analysis methods and finally, Section 3.4 elaborates on the theoretical background of the hypothesis tests.

## 3.1 Research method

Section 3.1.1. describes the Lean Six Sigma DMAIC method and Section 3.1.1 the Theory of Constraints.

### 3.1.1 Lean Six Sigma DMAIC

The DMAIC Lean Six Sigma (LSS) method improves the process performance by removing the waste of a process, e.g., overproduction, defects, or time due to unnecessary movements by an operator. Furthermore, a company is always striving for a constant production process. Therefore, the LSS approach also focusses on reducing the process variation. We discuss process variation further in Section 3.3. The LSS approach consists of five different stages which are the Define, Measure, Analyse, Improve, and Control phase, as shown in Figure 9. During the Define phase, the main activity is to explain the production process and elaborate on the specific subjects for the research (Atmaca, 2011).




*Figure 9: LSS DMAIC research cycle*

In the Measure phase, the measurement system is analysed, the current values are determined, and the points of improvement are provided. For the Analyse phase, the most important aspects are to identify the causes and determine the input variables. During the Improve phase, the optimal settings of the process are determined, and the solution will be implemented. After these results are implemented, the improvements should be validated. Finally, in the Control phase, the last checks should be done, conclusions should be provided, the report should be completed by writing a report (Atmaca, 2011). The LSS DMAIC approach is a suitable method for improving a production process, reducing defects, and minimizing process variation (Farrukh, 2021).

### 3.1.2 Theory of Constraints

Next to the LSS DMAIC approach, we could use the Theory of Constraints (TOC). This methodology focuses on the most important limiting factor that stands in the way of achieving the objectives of a company. This approach is also a Lean method. The goals are reached by systemically improving the bottleneck until it is no longer a problem. TOC consists of five different steps which are the identification of constraints, the use of constraints, subordination, increasing the throughput of constraint, and then return to the first step (Urban, 2019). Although this method seems applicable to our research, the method is not the approach we use in this study. The concept of TOC focuses on managing a process by first dealing with one constraint and then another (Urban, 2019). However, in our situation, the company does not have one specific bottleneck, but it desires to get a better understanding of the production process of fibre optics cable. This way, the company wants to improve the production process and reduce process variation.

During this research, we limit our focus to the Coating line where we first display the current performance and identify the variables that affect the attenuation value. Then, we define the points of improvement by analysing the system. Since the LSS approach is more suitable for a complete production process and the company is already familiar with the LSS DMAIC theory, we apply this method to the research to investigate whether it is possible to implement statistical analysis on the Coating line at TKF and reduce process variation. Furthermore, the LSS approach is a widely used methodology within the company and there are several Lean Six Sigma experts employed at the company.

## 3.2 Selection of statistical analysis method

The central question in this section is: '*Which statistical procedure is suitable to analyse the process of fibre optics cables?*'. As mentioned in Chapter 1, there is already software running on the Colour line at TKF. This software uses Statistical Process Control (SPC) to monitor the process variation. In order to investigate whether SPC is also proper for the Coating line, we conduct literature review. Furthermore, we study other statistical analysis methods to find the most suitable option. Besides, SPC, we point out two different options related to statistical analysis methods: Multivariate Statistical Process Control (MSPC), and the Multi-lot analysis method that uses multiple datasets to monitor the variability of the system.

SPC is the application of a statistical analysis method to monitor, control and optimize the system. By evaluating the performance of the process in real-time, the purpose is to operate at its full potential and create a Six-Sigma process (Madanhire, 2006). In a Six-Sigma process, the process encounters less than 3.4 errors per million productions of fibre optics reels. The first step of this analysis tool is to conduct a process capability and a process performance study. During these studies, the performance of the process will be measured, and furthermore, the number of Out-of-Control situations are being determined (Kahn et al., 1996). The control charts make it able to analyse and monitor if the system is In-Control. For a more detailed explanation of the capability studies and control charts, we refer to Section 3.3. The capability studies are also effective in the LSS DMAIC research cycle. Applying these studies to the Analyse, Improve and Control phases helps to detect whether the system has achieved the desired results with the implementation of SPC (Kahn et al., 1996).

Besides SPC we find the MSPC method. MSPC is a variant of the SPC method. However, we consider these methods jointly since there is no significant difference between SPC and the multivariate SPC method (Sánchez, 2008). The Multi-lot approach uses different data sets that are used to estimate the mean performance and part-to-part variability in order to monitor whether the system is In-Control. This way, it is possible to determine the statistical distribution of the dataset. By comparing the dataset with the proper distribution, the method enables it to identify an Out-of-Control (Ladbury, 2010).

The Multi-lot approach has overlap with the SPC since this method has almost the same approach as the SPC method. The first step is to determine the mean and the standard deviation of the data of the process. Then, the performance of the system is evaluated. Therefore, both approaches would be appropriate for the research. However, the Multi-lot method is not monitoring the Out-of-Control situations by using Control limits, but the Multi-lot method compares trends with the distribution of the dataset (Ladbury, 2010). This makes the SPC method the more advanced technique because the Control limits are especially calculated for the combination of Coating line, tube, and fibre. Furthermore, since SPC is already introduced in the company, and there is more detailed information about this procedure, the research focuses on the implementation of SPC.

## 3.3 Capability studies

The purpose of process capability and performance studies is to measure whether the process is capable to meet the customer specifications. Furthermore, these studies help to understand how constant a process is producing. These studies are quantified by the four different indices, these are: $C_p$, $C_{pk}$, $P_p$and $P_{pk}$ which we explain below. By using the performance and capability indices, we are able to indicate the process variation. These indices compare the process variation with the maximum acceptable variation of the process that is defined by the specification limits. So, a process with high specification limits or low process variation results in higher capability and performance indices because in this situation the process is better capable to produce within the specification limits. In total, we distinguish two types of variation, the common cause variation and special cause variation, as shown in Figure 10. The common cause variation is caused by shifts in the process (Lei, 2020). When the production process is less constant the shifts become larger. On the other hand, special variation is caused by e.g., bearings or a setting change on the production machine. This variation is also called a drift. The capability studies focus on the process variation in the short-term. Therefore, it takes only common cause variation into account. Process performance studies focus on the long-term. Here, we have changing circumstances, such as operators, input materials, process optimizations, etc. For this reason, process performance studies consider common and special cause variation (Lei, 2020).

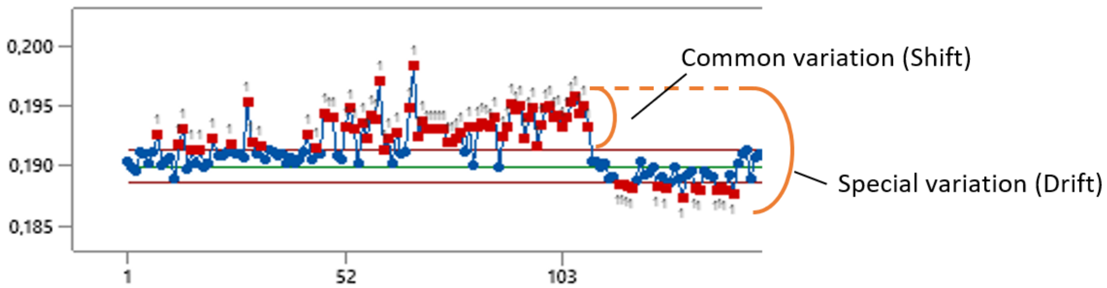



*Figure 10: Shifts and Drifts*

Table 6 demonstrates the relations between the specification width, Sigma level, defect rate, and process capability. The Sigma level determines the degree of performance of the production process. The higher the Sigma level of a process the better the process performs within the specification of the customer. This means that there are fewer parts per million (ppm) outside the specification limits, better known as the number of defects and the Percent of defective (Theisens, 2018). However, in theory, it is possible to achieve a Sigma level above 6, in practice, it will not encounter. Therefore, we do not consider a higher Sigma level than 6 in this research. Next to this, the specification width says something about the maximum tolerated variation in the process with respect to a certain Sigma level. Since the capability indices do not consider changing circumstances and the performance indices do, the specification width for the performance indices is larger than for the capability indices (Deleryd, 1998). The final column shows which capability or performance index value is related to every Sigma level.

*Table 6: Six Sigma metrics, process capability and performance (Theisens, 2018)*

| | Sigma level | Specification width | ppm outside spec | Percent defective | Capability / performance index |
|---|---|---|---|---|---|
| *Capability* | 1 | 1σ | 317,311 | 31.7% | 0.33 |
| | 2 | 2σ | 45,500 | 4.55% | 0.67 |
| | 3 | 3σ | 2,700 | 0.27% | 1.00 |
| | 4 | 4σ | 63 | 0.0063% | 1.33 |
| | 5 | 5σ | 0.57 | 0.00006% | 1.67 |
| | 6 | 6σ | 0.002 | 0.000002% | 2.00 |
| *Performance* | 1 | 2σ | 691,462 | 69% | -0.17 |
| | 2 | 4σ | 308,538 | 31% | 0.17 |
| | 3 | 6σ | 66,807 | 6.7% | 0.50 |
| | 4 | 8σ | 6,210 | 0.62% | 0.83 |
| | 5 | 10σ | 233 | 0.023% | 1.17 |
| | 6 | 12σ | 3.4 | 0.00034% | 1.50 |

Then, we have $\sigma_{within}$ and $\sigma_{overall}$. Because the capability indices measure the system in the short-term, it considers only the process variation for a specific period without changing circumstances, this is the $\sigma_{within}$. On the other hand, performance indices measure process variation in the long-term. Therefore, the $\sigma_{overall}$ takes the complete process variation into account, including common and special variations (Theisens, 2018).

The $C_p$ index is a statistical measure to quantify the process performance in the short-term. The $C_p$ compares the process variation width with the maximum variation that is allowed according to the specification limits. Therefore, it only considers the common cause process variation, thus the shifts (Deleryd, 1998). For this index, the following formula is established:

$$C_p = \frac{Specification\ width}{Process\ width} = \frac{USL - LSL}{6 \cdot \sigma_{within}}$$

*Equation 1: Process capability Cp*

Besides the $C_p$ index, the $C_{pk}$ value is also an indication of the process capability. In contrast to the $C_p$ index, the $C_{pk}$ takes both, the variability, and the mean into account. Besides the degree of process variation, the $C_{pk}$ index determines whether the mean of the process variation lies in the centre between the two specification limits or closer to one of these values. This means that this value also tells how close a process is running to its nearest specification limit (Deleryd, 1998). The $C_{pk}$ can be identified by using the following formula:

$$C_{pk} = \min(C_{pL,}C_{PU}) = \min(\frac{\bar{X} - LSL}{3 \cdot \sigma_{within}}, \frac{\mathrm{USL} - \bar{X}}{3 \cdot \sigma_{within}})$$

*Equation 2: Process capability Cpk*

To measure the process performance, the $P_p$ and $P_{pk}$ performance indicators are used. These indices are very comparable to the capability indices, $C_p$ and $C_{pk}$. However, these indices focus on long-term process performance since they take process variation over a longer period into account. The $P_p$ index considers only the variability and the $P_{pk}$ takes the variability and the mean into consideration (Deleryd, 1998). For these values, the following formulas are established:

$$P_p = \frac{Specification\ width}{Process\ width} = \frac{USL - LSL}{6 \cdot \sigma_{overall}}$$

*Equation 3: Process performance Pp*

$$P_{pk} = \min(P_{pL,}P_{PU}) = \min(\frac{\bar{X} - LSL}{3 \cdot \sigma_{overall}}, \frac{\text{USL} - \bar{X}}{3 \cdot \sigma_{overall}})$$

*Equation 4: Process performance Ppk*

Next to the capability studies, we use a process control chart to demonstrate how a process changes over time. A control chart consists of a centre line for the average and an upper and lower line for the control limits. These lines are determined by using historical data of the process (Theisens, 2018). There are different kinds of control charts. This study uses the Xbar- and R-charts and I- and MR-charts. First, the Xbar- and R-charts. The Xbar-chart shows the difference between the mean values over time and the R-chart provides the difference of the range overtime. The range is determined by taking the maximum minus the minimum of a subgroup. In this research, every tube is a different subgroup since all the fibres in the tube belong to one specific subgroup. So, if a tube consists of 12 fibres, the range of the attenuation value is the maximum minus the minimum of these 12 values. When there is no subgroup, the I- and MR-charts are used. The I-chart shows the absolute value of a given value. The MR-chart shows a difference with respect to the previous batch (Theisens, 2018).

For the research on the attenuation value of fibre optics, the data is measured continuously. Furthermore, since the number of fibres (n) in the tube could vary between 2 and 24 both control charts as mentioned above are used, the Xbar- and R-charts and I-and MR-charts. Figure 11 and Figure 12 below provides an example of the two charts, where the Out-of-Control situations are marked in red. A popular software for the calculation of these graphs is Minitab. Along with SPSS is Minitab one of the leading statistical software packages and is ideal for analysing quality improvement data. Furthermore, Minitab enables it to, e.g., plot graphs, conduct capability analyses and calculate the basic statics of a dataset (Ozgur, 2017). We use the Minitab statistical software throughout the whole research.

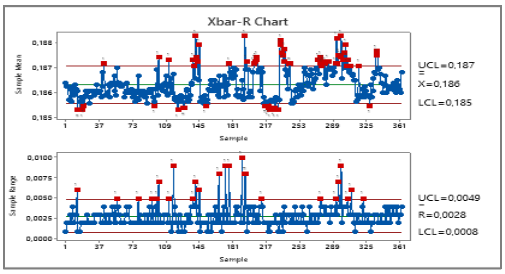



*Figure 11: Example of  Xbar- and R-charts*

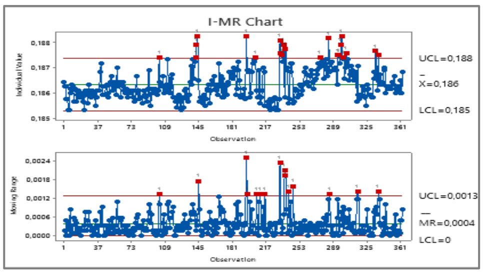



*Figure 12: Example of  I- and MR-charts*

## 3.4 Hypothesis test

In order to verify whether we can use the calculated control limits for multiple tubes and Coating lines, i.e., RQ3, we plan to conduct hypothesis testing to determine the probability that a given statement is true. Hypothesis testing consists of multiple steps which start with the formulation of the null hypothesis and an alternative hypothesis. Next, the type of test has to be selected, and the choice of the acceptable significance level should be determined. Finally, the probability of the value has to be calculated and then these values can be compared. This research uses a 5% level of significance ($\alpha = 0.05$) that means that when the p-value becomes less than 0.05, the null hypothesis has to be rejected and so we cannot assume equal control limits for different tubes and Coating lines (M.C.Pereira, 2009).

In order to test whether it is possible to use equal control limits for different variables, two types of hypothesis tests are suitable. The first test is the two-sample t-test. This test determines whether there is a difference between the means of two samples. The other test is the test for equal variances. This test is used to compare the variances with each other. For this test, we can use two different methods, the Bonett's test and the Leven's test. However, Bonett's test is more powerful than Leven's test when the sample size is greater than 20 and the dataset tends to a normal distribution (Theisens, 2018).

## 3.5 Conclusion

Lean Six Sigma is a suitable methodology for enhancing the environment of a production process. The LSS methodology focuses on different elements of the production process and consists of five different research phases. In this way, the purpose is to improve the process and reduce process variation. In order to determine the performance of a process regarding the number of failures in a system and the process variation, the capability studies a proper way to measure it. The capability can be determined for the short term and for the long term. In the short term, the Cp index is used which provides information about the common variation within a process. In the long-term, the Ppk index is recommended since this index gives the user information about common and special variations. A hypothesis test can be conducted to verify whether there is a significant difference between the mean and variability for the two samples. By conducting a t-test or a test on equal variances the difference in mean and variability can be assumed or not. Finally, a statistical analysis method is applicable to discover patterns between consecutive reels and detect process variation. A commonly used statistical analyse method is SPC. SPC offers the ability to constantly monitor the process and check whether the process is in control.

# 4. Statistical evaluation of the production process

In this chapter, we discuss the Measure phase of the research. Here, we elaborate on the following research questions identified by RQ3 and RQ4:

RQ3: "What is the baseline performance of the coating process?"

RQ4: "To which extent is it possible to standardize the control limits for different types of tubes and Coating lines?"

We divide this problem into the following sub-questions:

- "How does the measurement system perform?"
- "What are the statistical characteristics of the fibres?"
- "What is the current performance of the Coating lines?"
- "To which extent have the different types of fibres an impact on the attenuation value?"
- "To which extent have the different Coating lines an impact on the attenuation value?"

In Section 4.1, we start with the measurement system, then in Section 4.2, we explain the statistical characteristics of the different samples. Section 4.3 starts with the process capability. Here, we discuss the current performance of the Coating lines 'SeC 6' and 'SeC 9' and calculate the control limits for different fibres and Coating lines. Then Section 4.4 provides an analysis of whether the different types of fibres influence the attenuation value. Finally, in Section 4.5 we investigate whether the different Coating lines influence the attenuation value in order to determine whether it is possible to standardize the control limits.

## 4.1 Measurement system

In this section we treat reliability and validity of the measurement system. Section 4.1.1 starts with a Measurement System Analysis. Then, Section 4.1.2 explains the influence of the position of a fibre. Finally, Section 4.1.3 discusses the incorrect measurements.

### 4.1.1 Measurement System Analysis

A Measurement System Analysis (MSA) determines the precision of the measurement equipment and measures the influence of an operator or procedure. During each measurement, there is a certain variation caused by the measurement system or through the inaccuracy of the person who is measuring. To gain a better insight into the performance of the measurement system at TKF, we conduct an MSA. There are different types of MSA. In this research, we use the Gage Repeatability and Reproducibility (R&R) study since we make use of quantitative data. The Gage R&R study is used to assess the measurement system variation relative to the tolerances of the specifications limits and process variation, also known as precision (Woodall, 2007). The precision of the measurement is affected by three different elements: Repeatability, Reproducibility, and Uniformity of the system. Repeatability affects the amount of variation caused by the measuring instrument itself. On the other hand, we encounter Reproducibility by measurement procedure, different operators, and other circumstances. Uniformity tells which extent measurement variation is uniform over all measurements (McNeese, 2018). Finally, the MSA focuses on the stability of the process. The norm for an acceptable measurement system follows from the Automotive Industry Action Group (AIAG) (McNeese, 2018). The AIAG has determined four different criteriums: Tolerance, Study variation, Contribution, and Discrimination. The Tolerance indicates how precise the data lies between the specification limits.

Study Variation indicates the ratio of the standard deviation caused by the measurement system or changing circumstances. The Contribution is the ratio of the total variance caused by a certain element of this study and the Discrimination indicates the number of distinct categories. So, how many parts the measurement system can be distinguished. According to the norm determined by the AIAG, the Tolerances and Study variation should lie under 20%, the contribution should lie under 7% and the Discrimination has to be greater than 7 for an acceptable measurement system (McNeese, 2018). These norms are the guidelines. However, a company must decide on its own which norms to apply and when a measurement system is acceptable or not. TKF strives to meet these norms for the measurement systems. Nonetheless, if the measurement system cannot meet these norms, then it is not a major issue, but it indicates that there is space for improvement.

As mentioned in Section 2.3, at TKF, we have two different ways of measurement for the Coating line. First the MiniMAS, this system is connected to the OTDR measurement system and can measure a total of 24 fibres simultaneously. A coupler will automatically go through all the fibres that have to be measured. Next to this, when an operator uses the manual MAS, he can only measure one fibre at a time which takes longer. A previous MSA study has already proved the reliability and validity of this measurement system following the acceptance standards defined by the AIAG. This student conducted an MSA on two manual MAS systems. The first MSA provided a Tolerance of 11%, a Study variation of 17%, a Contribution of 3% and the Discrimination is equal to 7. The second MSA gives us the values of 7% on Tolerances, 11 on Study variation, 1% on Contribution and a Discrimination of 12 (Slomp, 2021). So, with these studies, the student has proved that the manual MAS can meet the acceptance standards.

In the following MSA, we take 10 different reels, 3 operators and each operator measures the reels 2 times. Then, we compare these studies with each other and investigate the accuracy, precision, and stability. If we examine the results of the MSA studies on the MiniMAS in Table 7, we find that the OTDR measurement system is not valid and reliable. The MSA exhibits that the MiniMAS scores far below the AIAG standards on every criterion, except the Tolerances. The boxes in the table prompt red if the value is below the acceptance standards and green if they meet the AIAG standards. However, as mentioned earlier the actual performance of the tolerance is hidden by the large specification limits on the attenuation value. Therefore, it is not astonishing that the MSA's score is good in this field. The Study variation is 5 times as high as the acceptance standards for almost every fibre. Reasons for this deviation can be relative to the accuracy and sensitivity of the measurement system. Next, if we compare the Contribution with the AIAG standards, we find that the values from the table are at least 5 times larger. This means that the measurement system also fails to meet this criterion. Finally, we find for every fibre a Discrimination of 1 which is also extremely low. With a more accurate system, it should be possible to score at least a discrimination of 7, as the AIAG standards prescribe.

*Table 7: Analysis of the acceptance standards for the MSA study*

| | Tolerances | R&R Study Variation | Contribution | Discrimination |
|---|---|---|---|---|
| *MSA Fibre 1* | 5.49% | 83.59% | 69.87% | 1 |
| *MSA Fibre 2* | 5.23% | 85.88% | 73.76% | 1 |
| *MSA Fibre 3* | 8.03% | 85.83% | 72.91% | 1 |
| *MSA Fibre 4* | 5.78% | 75.14% | 56.46% | 1 |
| *MSA Fibre 5* | 7.78% | 81.48% | 66.39% | 1 |
| *MSA Fibre 6* | 5.58% | 87.78% | 77.05% | 1 |

| | | | | |
|---|---|---|---|---|
| *MSA Fibre 7* | 6.62% | 98.24% | 96.51% | 1 |
| *MSA Fibre 8* | 6.30% | 73.19% | 53.56% | 1 |
| *MSA Fibre 9* | 6.30% | 71.11% | 50.57% | 1 |
| *MSA Fibre 10* | 10.67% | 90.49% | 81.88% | 1 |
| *MSA Fibre 11* | 6.46% | 73.69% | 54.31% | 1 |
| *MSA Fibre 12* | 7.76% | 76.55% | 58.60% | 1 |

Since we cannot demonstrate an acceptable measurement system for a single fibre with the current AIAG acceptance standards, we conduct an MSA on the average of the 12 fibres. For this MSA, we use 8 parts, 3 operators, and 2 replications. Table 8 shows how the measurement system performs among the four criteria. However, also for this MSA, we cannot demonstrate the reliability and validity of the measurement system because we find non-conforming values for the Study variation, Contribution and Discrimination.

*Table 8: Analysis of the acceptance standards for the MSA study on average*

| | Tolerances | R&R Study Variation | Contribution | Discrimination |
|---|---|---|---|---|
| *MSA Avg. 8 parts* | 3.04 | 68.06 | 46.32 | 1 |

So, to conclude, with the current acceptance standards based on AIAG (McNeese, 2018), we cannot prove that the MiniMAS system is accurate, precis and stable to measure the attenuation value of fibre optics.

### 4.1.2 Fibre position

*Figure 13: Slots for the measurement of the fibre*

Although, we cannot demonstrate the reliability and validity of the MiniMAS, we want to research whether the position of the fibre in the measurement system matters. When an operator is measuring the fibres, the fibres can be measured in different sequences or positions. For instance, considering a tube with 12 fibres, these 12 fibres could be measured on 12 different slots, as shown in Figure 13. To verify, whether the position of these fibres has an influence, we compare the data for the first 20 weeks of 2022 to investigate whether the position of the fibre matters. For this check, we carry out an ANOVA study where we perform a test on the difference in mean and variability. In total, we run three different tests with the V29-Fibre on two different measurement stations, the 'MiniMAS 7' and 'MiniMAS 9'.

For the first test, we test the fibres for different means with a 5% level of significance ($\alpha = 0.05$). In this test, the null hypothesis states that all means are equal, and the alternative hypothesis states the contradiction. Table 9 shows that for the 'SeC 6' and 'SeC 9 ' all p-values are higher than 0.05. This implies that we cannot reject the null hypothesis for these measurement systems. So, we do not have enough evidence to assume a different mean between the 12 positions.

*Table 9: ANOVA tests means measurement stations*

| Coating line | Measurement station | N | DF | Mean | Standard deviation | p |
|---|---|---|---|---|---|---|
| SeC 6 | MAS7 (V29) | 357 | 11 | 0.18686 | 0.000014 | 0.406 |
| SeC 9 | MAS7 (V29) | 138 | 11 | 0.18652 | 0.000016 | 0.499 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | MAS9 (V29) | 354 | 11 | 0.18717 | 0.000010 | 0.780 |

Besides the test for equal means, we conduct a test for equal variances. For this test, we use the same level of significance ($\alpha = 0.05$). Table 10 shows that the results are similar to the means test. The p-values are higher than 0.05 for all the tests. For the test on equal variances, we can use two methods (Section 3.4). However, Bonett's comparisons test is more powerful than the Levene test with a sample size above 20 (Theisens, 2018). Therefore, we use the Multiple comparisons test for this research. Since all p-values are above 0.05, we conclude for all measurement systems that we cannot reject the null hypothesis for the measurement station at a 5% level of significance.

*Table 10: ANOVA tests variances measurement stations*

| Coating line | Measurement station | Method | Test Statistic | p-value |
|---|---|---|---|---|
| *SeC 6* | MAS7 (V29) | Multiple comparisons | - | 0.619 |
| | | Levene | 0.71 | 0.726 |
| *SeC 9* | MAS7 (V29) | Multiple comparisons | - | 0.287 |
| | | Levene | 0.53 | 0.882 |
| | MAS9 (V29) | Multiple comparisons | - | 0.555 |
| | | Levene | 0.58 | 0.846 |

We also want to know if there is a difference between the fibres which are measured on the manual MAS and the fibres of the MiniMAS. For this study, we take the V29-Fibres of the 'SeC 6' since these sample sizes are approximately the same and it is important to use fibres from the same production line for the tests. First, we conduct a test on different means with a 5% level of significance ($\alpha = 0.05$). The test for different means provides us with a p-value equal to 0.000, which means that we reject the null hypothesis and that there is a significant difference between the mean of the manual MAS and the mean of the MiniMAS. For the test of equal variances, we find a p-value of 0.772. Therefore, we cannot reject the null hypothesis at a significance level of 5%. Since we can still not prove equal means between both samples, it is also not possible to prove the reliability and validity of the MiniMAS by comparing it with the MAS.

### 4.1.3 Measurement failures

In Section 4.1.1, we demonstrated that the MiniMAS is unreliable. However, we also encounter issues that are caused by other factors. To determine the reasons for these errors, we define the Key Process Input Variables (KPIVs). These KPIVs have an impact on the results of the Key Process Output Variables (KPOVs) (Theisens, 2018). The KPOVs of the measurement procedure are the attenuation value and the length of the fibres. However, this research focuses only on the attenuation value. The aim of these variables is to find the root causes of the measurement errors. In total, we consider four different KPIVs: Operator, Material, Machine, and Environment. At first, the measurement errors caused by the operators. During the execution of the MSA, we observed a lot of measurement failures. To gain a better insight into this number, we calculate the number of errors by calculating the First Time Right (FTR) percentage. The FTR provides us with the percentage of measurements which are performed correctly. After inspection of the data from the first 20 weeks of 2022, we find the following values in Table 11 regarding the incorrect measurements. In Table 11, we see a relatively low FTR percentage for actually every fibre. The total FTR percentage is equal to 81.47%. In fact, manufacturers are striving for an FTR percentage of 100%.

*Table 11: FTR percentage of measurements*

| Coating line: | | Lower limit (dB/km) | Upper limit (dB/km) | Estimation Incorrect measurement (tubes) | Total production weeks 1-20 (tubes) | FTR (%) |
|---|---|---|---|---|---|---|
| *SeC 6* | V28 | 0.185 | 0.205 | 32 | 152 | 78.95 |
| | V29 | 0.185 | 0.195 | 171 | 1217 | 85.95 |
| *SeC 9* | V29 | 0.185 | 0.195 | 354 | 1769 | 79.99 |
| | V30 | 0.185 | 0.195 | 121 | 521 | 76.78 |
| | | | Total: | *678* | *3659* | *81.47* |

Figure 14 exhibits an example of an error caused by an operator during the measurement procedure of the attenuation value. This figure demonstrates a failure with the connection between the fibre and the measurement system. Although the measurement is incorrect, on the right side of the figure, we find that every box is 'OK' and prompt green.

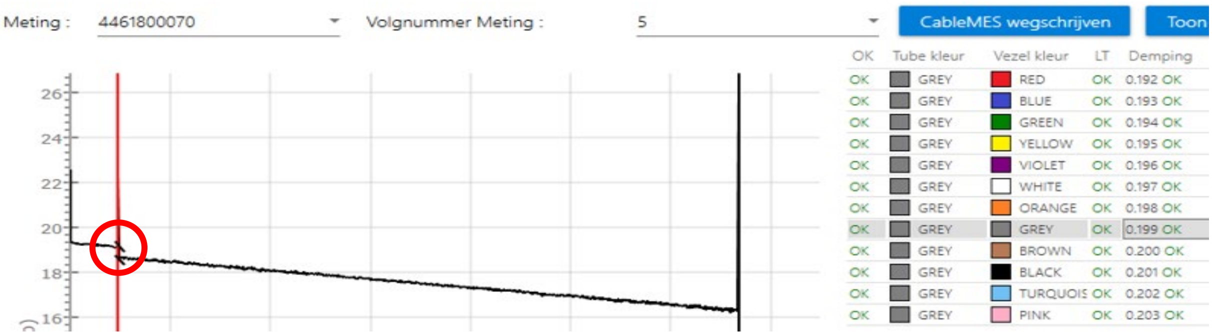


*Figure 14: Connection error*

Figure 15 shows another error due to a human failure. This figure shows high variability in the graph which causes an incorrect measurement. Nevertheless, on the right side of the figure, we see that the attenuation (Demping) values are good enough. So, probably, the operator has only considered the column of the attenuation. Next to this, sometimes it occurs that the operators forget to change the settings for a cable with a shorter length. In this way, the measurement system will also measure an incorrect value for the attenuation. These poor measurements can be caused by insufficient education or control of the staff.

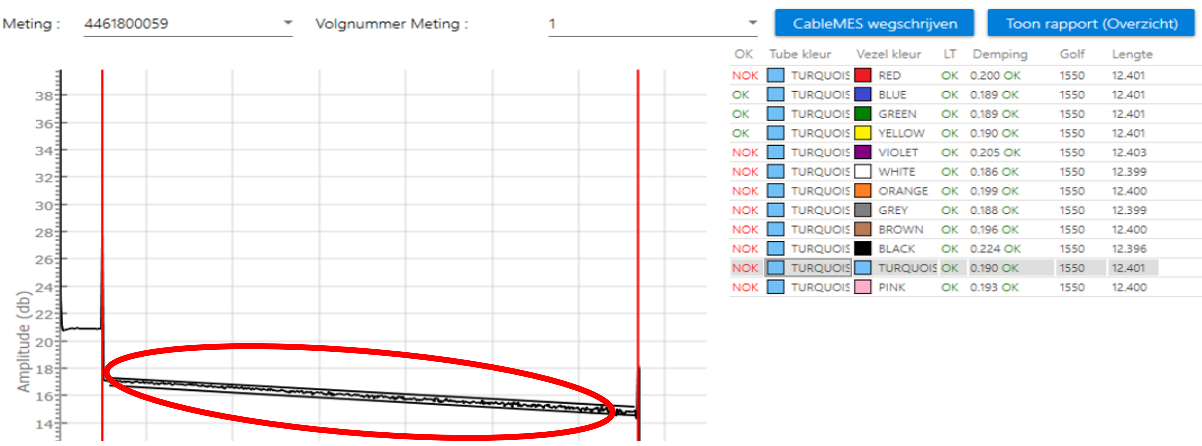


*Figure 15: High variability error*

Next to this, we observe something remarkable regarding the materials. From Table 11, we remark that the V29-Fibre has fewer failures than the other two fibres. Compared with the V28-Fibre, the V29-Fibre has a better quality since it is an A2-Fibre. Besides, the V30-Fibre has also a lower FTR percentage than the V29-Fibre. This finding can be the result of a smaller diameter since a smaller diameter is harder to measure. As mentioned in Section 2.1, the diameter of the V29-Fibre is 234 µm and the diameter of the V30-Fibre is just 190 µm.

Also, we come across failures in the measurement machine itself. Often this is caused by poor maintenance, for instance Figure 16. This figure shows that the connector is measuring fibre 10. In fact, according to the system it should measure fibre 11. So, the measurement instrument is not calibrated.

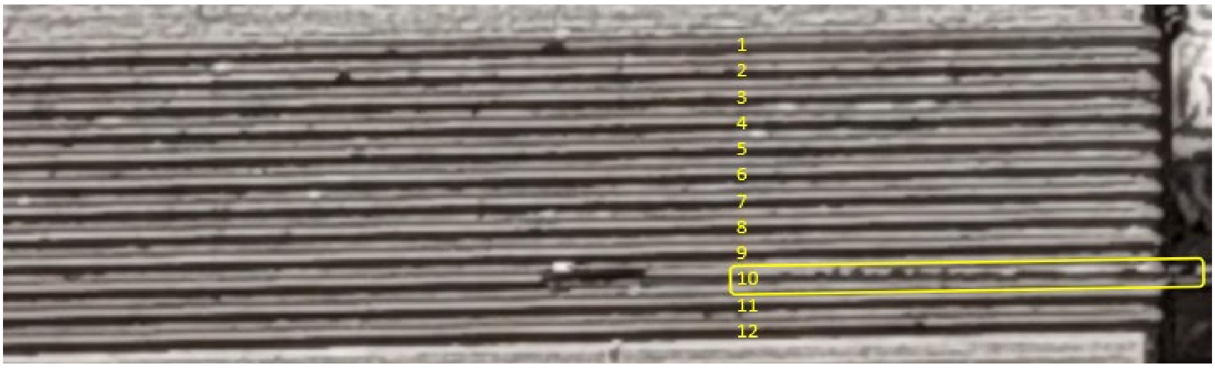



*Figure 16: Incorrect position*

Concerning the environment, we observe that the work environment is often unorganized. As shown in Figure 17, we see that the workspace is unstructured, and there is no fixed place for the tools and equipment. Often things are lost or get dirty due to poor maintenance. This causes extra unnecessary movements and is extremely inefficient because operators first have to look for the right equipment before they can measure.

*Figure 17: Measurement station at TKF*

## 4.2 Statistical characteristics

As mentioned in Section 2.1, we consider three different types of fibres, the V28-Fibre, the V29-Fibre, and the V30-Fibre. We investigate these fibres on two separate Coating lines, the ‘SeC 6’ and ‘SeC 9’. The fibres are all surrounded by a Soft Tube. The graphical charts of Appendix A.2 give the following statistical characteristics for the V28-, V29 and V30-Fibres, these values are summarized in Table 12. For the standard deviation, the difference between the V29-Fibres of the ‘Sec 6’ and ‘SeC 9’ is negligible since these values are 0.00267 and 0.00245, respectively. The standard deviations of the V28-Fibre of the ‘SeC 6’ and the V30-Fibre of the ‘SeC 9’ are slightly higher, 0.00342 and 0.00304. The difference in the standard deviation could be the result of a smaller sample size. For the skewness and kurtosis, we also remark a difference: From Table 12, we see that the V29-Fibre of the ‘SeC 9’ has a relatively high skewness and kurtosis compared with the ‘SeC 6’. Reasons for this difference could be the age of the machines since the ‘SeC 9’ is nearly 7 years newer than the ‘SeC 6’. Because the ‘SeC 6’ is the older machine, it is more sensitive to failures and wear. Furthermore, we observe a significant difference in sample size between the V28-Fibre of the ‘SeC 6’ and the V30-Fibre of the ‘SeC 9’, and the V29-Fibres. The sample size of the V29-Fibre is larger than the V28- and V30-Fibres. So, this means that the results for the V29-Fibres are more reliable than those for the V28- and V30-Fibres.

In order to conduct capability and performance studies for the Coating lines, it is essential to analyse if the process is stable. Additionally, it is important to know whether the process is normally distributed. From the graphical summaries in Appendix A.3, we find that every process is stably producing. For a normal distribution, the skewness of a dataset should be within the limits of -2 and +2, and the kurtosis within -7 to +7 (Theisens, 2018). Tables 24 and 25 indicate that none of these datasets fits the normal distribution. For that reason, we check whether there is a distribution that fits the dataset by conducting an Anderson-Darling (AD) test. By performing an Anderson-Darling test (Jäntschi, 2018), we compare the empirical cumulative distribution of the sample data with the expected cumulative distribution. In this test, the null hypothesis states that the population is distributed according to the tested distribution. The alternative hypothesis states that the distribution does not fit. If the p-value of this test is lower than 0,05, the null hypothesis is rejected. Otherwise, we assume that the distribution fits the dataset (Jäntschi, 2018). In total, we performed the Anderson-Darling test on 14 different distributions. However, none of these distributions fit these datasets since the p-value for all the tests is lower than 0.05. We refer to Tables 24 and 25 of Appendix A.3 for a complete overview of all the Anderson-Darling tests.

*Table 12: Statistical characteristics data Coating lines TKF*

| | Type of fibre: | N*12: | Mean | St. Dev. | Skewness | Kurtosis |
|---|---|---|---|---|---|---|
| *SeC 6* | ST002 / V28 | 1,918 | 0.188 | 0.00342 | 4.0 | 26.3 |
| | ST002 / V29 | 14,572 | 0.187 | 0.00267 | 4.4 | 46.1 |
| *SeC 9* | ST002 / V29 | 21,024 | 0.187 | 0.00245 | 5.8 | 68.4 |
| | ST004 / V30 | 6,168 | 0.190 | 0.00304 | 2.6 | 16.5 |

Last in Table 13, we calculate the statistical characteristics for the dataset without the incorrect measurements. In this table, we find values that fit better the properties of a normal distribution, e.g., the V29-Fibre produced on the 'SeC 6' with skewness of 1.1 and kurtosis of 2.6. However, we still cannot assign a clear distribution to the dataset. Therefore, in consultation with the supervisor of TKF and based on the common use of the normal distribution in the literature regarding similar studies, we assume that the data is normally distributed for all of the datasets used in this study.

*Table 13: Statistical characteristics data Coating lines TKF without incorrect measurements*

| | Type of fibre: | N*12: | Mean | St. Dev. | Skewness | Kurtosis |
|---|---|---|---|---|---|---|
| *SeC 6* | ST002 / V28 | 1,452 | 0.188 | 0.00245 | 3.9 | 28.2 |
| | ST002 / V29 | 7,015 | 0.187 | 0.00113 | 1.1 | 2.6 |
| *SeC 9* | ST002 / V29 | 4,288 | 0.187 | 0.00116 | 1.2 | 3.6 |
| | ST004 / V30 | 5,890 | 0.190 | 0.00204 | 0.5 | 0.0 |

## 4.3 Process capability

As said earlier in Section 3.3, we conduct several process capability and performance studies during this research, in order to measure the current performance of the Coating lines at TKF. The purpose of these studies is to calculate the lower control limit (LCL) and upper control limit (UCL) for the implementation of SPC for different tubes and Coating lines (Jalote, 2002). Furthermore, with these studies, we investigate whether it is possible to standardize these values for the different tubes.

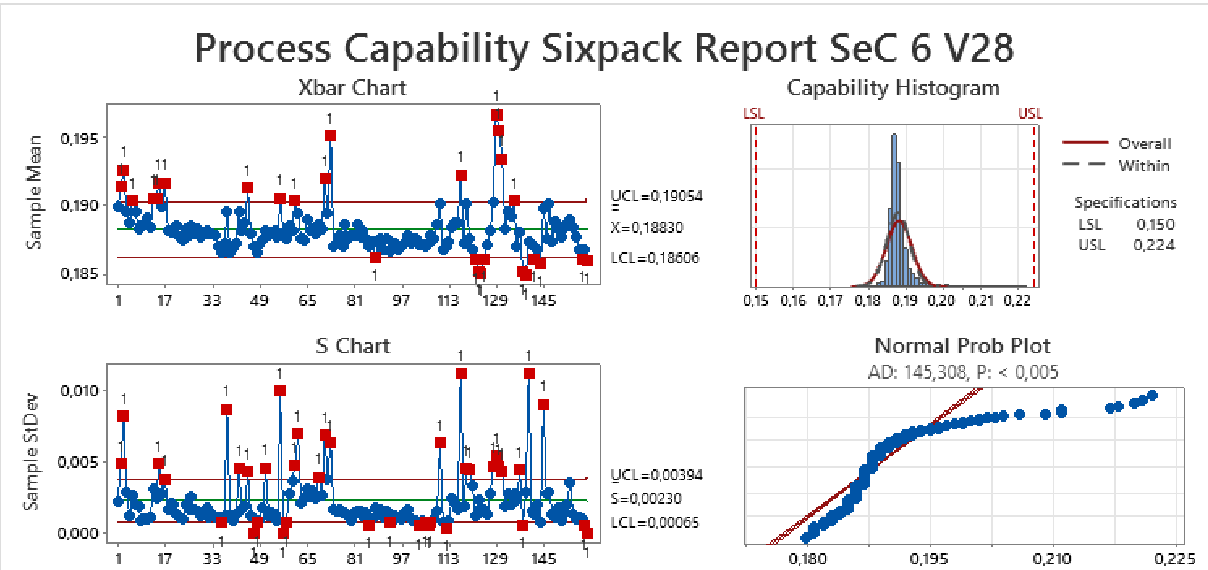
During the study, we use four different datasets of the Coating lines 'SeC 6' and 'SeC 9'. First, we distinguish the data of the 'SeC 6' between the V28-Fibre and the V29-Fibre. Next to this, we use the datasets of the V29- and V30-Fibres produced on the 'SeC 9'. All these fibres are surrounded by a Soft Tube. For these capability analyses, we use the datasets including the measurement errors discussed in Section 4.1. Although the reliability and validity of the MiniMAS is not proven, we do use this data of the MiniMAS since the purpose of this stage is to analyse the current process performance, and these measurement errors are part of the current performance. This way, we can give an acceptable estimation of the current performance of the production process. Furthermore, we compare these capability studies with the studies in Section 5.2. In this section, we conduct capability studies under the condition of a reliable measurement system. This way, we are able to analyse the influence of the measurement procedure and calculate the actual performance of the process.

Besides the different sorts of fibres and Coating lines, we could also distinguish the different types of the colour layer around the transparent fibre and the number of rings printed on the fibres. These colour layers and printed rings serve as an identification element when the installers are placing the fibre optics cable. However, previous studies have shown that these elements have negligible influence on the attenuation value for the V28-, V29-, and V30-Fibres. For that reason, we distinguish only the three different types of fibres for this study (Kost, 2021).

### 4.3.1 SeC 6 Process capability

The process capability studies on the 'SeC 6' focus on the V28- and V29-Fibres. For these studies, we only focus on the capability of the attenuation.

In Figure 18, we find the capability sixpack of the V28-Fibres surrounded by a Soft Tube with an outside diameter of 1.30 mm and an inside diameter of 1.00 mm. The capability sixpack demonstrates on the left the final 25 measurements on the Xbar-chart. On the right, it exhibits the histogram of the dataset, a normality check, and the capability indices. These tubes have been produced at the Coating line 'SeC 6'. If we take a closer look at the sixpack, the sixpack shows that capability of the fibre on attenuation is relatively high. This is supported by the $C_p$, $C_{pk}$, $P_p$and $P_{pk}$values, which are 4.04, 3.90, 3.60, and 3.48, respectively. These values indicate that the Sigma level is above 6 since the specification width for capability is larger than 6 Sigma and for performance larger than 12 Sigma. Next to this, we see that the process is relatively stable since the average standard deviation is less than 0.05, and besides, there is a peak in the histogram for the attenuation value of 0.187 dB/km. The defect rate of the line is 0.00 PPM. That means that no defects with the product will occur for every million parts. This rate is extremely low and could indicate that the current specification limits are too high. However, the Xbar-charts exhibits relatively many red bullet point, which indicates an Out-of-Control. So, there is space to improve.



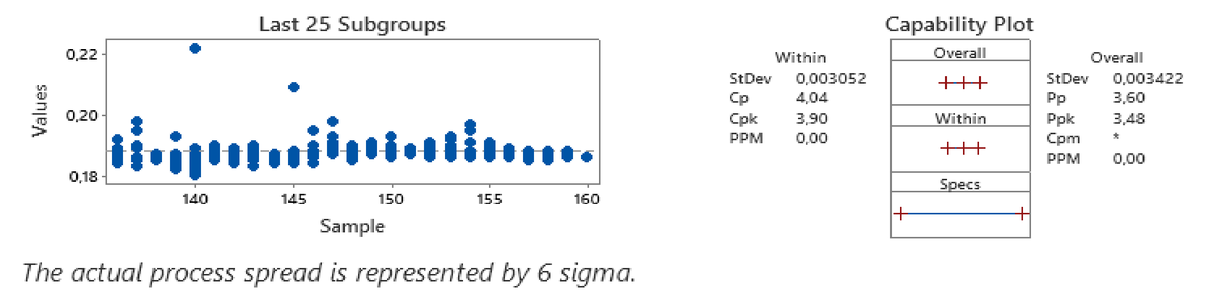



*Figure 18: SeC 6 V28 weeks 1-20 2022 1550 nm / ST002 Ø1.30/1.00 /  161 Tube*

Figure 19 exhibits the capability sixpacks of the V29-Fibre. In Figure 19, we see the data of the attenuation of weeks 1 to 20 of 2022. The V29-Fibre is also surrounded by a Soft Tube with an outside diameter of 1.30 mm and an inside diameter of 1.00 mm. These tubes have been produced at the Coating line 'SeC 6'. Also, this sixpack shows that the capability of the V29-Fibre is extremely high. This means that the Sigma level also for the V29-Fibre on the 'SeC 9' is above 6 because the $C_p$, $C_{pk}$, $P_p$ and $P_{pk}$ are 7.09, 7.01, 4.44 and 4.38, respectively. Due to the high specification limits set up by the research and development department of TKF, the capability indices become high. However, with the implementation of SPC on the Coating line we also calculate new control limits which result in lower and more sensible capability values. Next to this, on average, the process is relatively stable since the average standard deviation is less than 0.002, besides there is a peak in the graph for the attenuation value is around 0.186 dB/km. The defect rate for this tube is equal to 0.00 PPM which indicates that the specification limits are also too wide for this type of fibre.

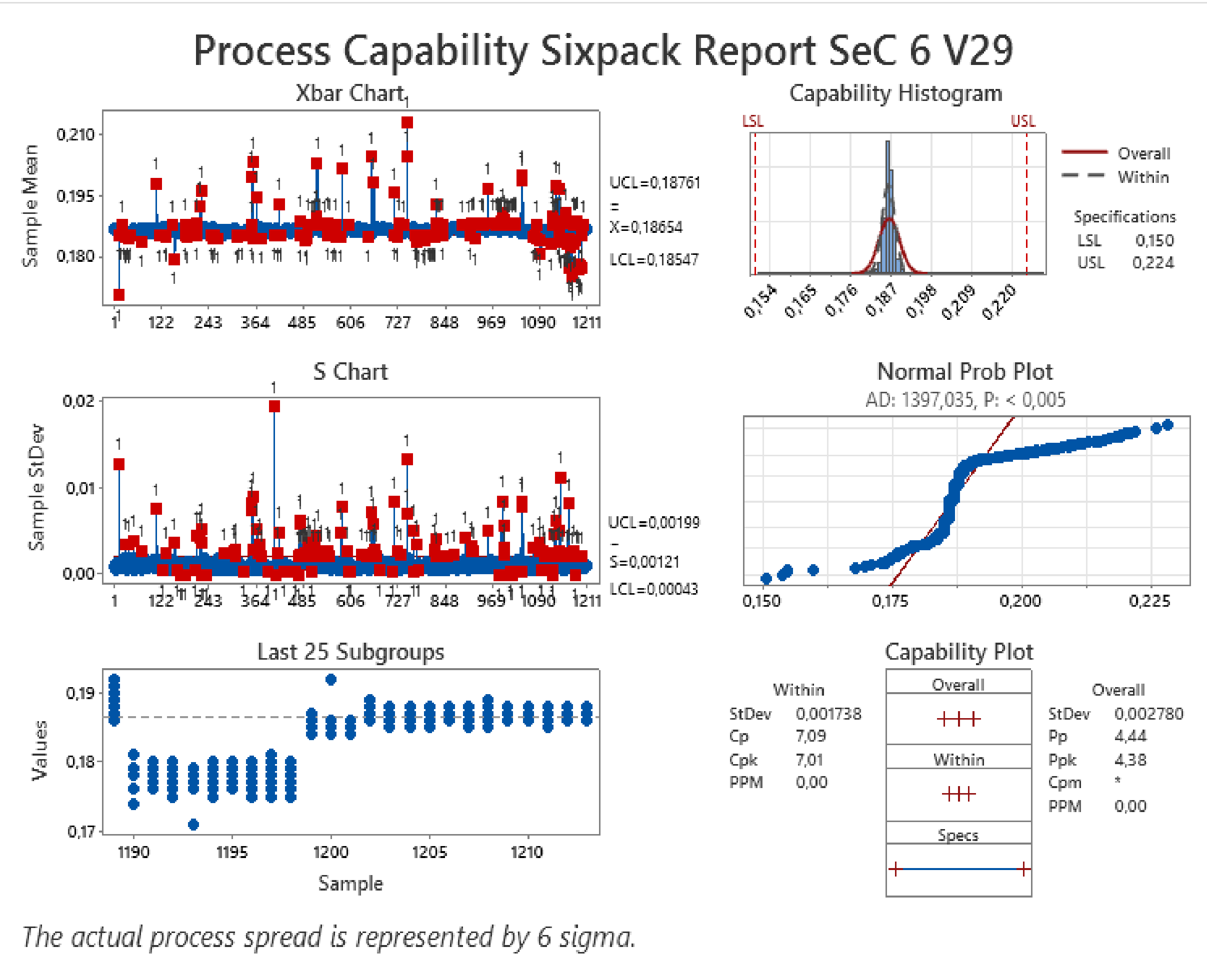



*Figure 19: SeC 6 V29 weeks 1-20 2022 1550 nm / ST002 Ø1.30/1.00 / 1215 Tube*

## 4.3.2 SeC 9 Process capability

For process capability studies on the 'SeC 9', we inspect the V29- and V30-Fibres. These fibres are provided with a Soft Tube on the Coating line. First, the capability of the V29-Fibres is discussed and then the V30-Fibres.

In Figure 20, we find the capability sixpacks of the V29-Fibre of the 'SeC 9'. This figure uses the data of the attenuation for weeks 1 to 20 of 2022. When we take a closer look at the figure, we notice the $C_p$, $C_{pk}$, $P_p$and $P_{pk}$ values of 6.06, 6.03, 5.04 and 5.01, respectively. Even as for the other tubes, these indices are extremely high. Therefore, this tube has a sigma level of more than 6. However, when we inspect Figure 20, we observe a lot of Out-of-Control situations. The introduction of SPC could prevent these out-of-control situations because SPC shows immediately if a reel is Out-of-Control or not. This way, a manager knows whether he has to take action to get the system back in control. Next to this, there is a defect rate of 0.00 PPM which indicates too wide specification limits.

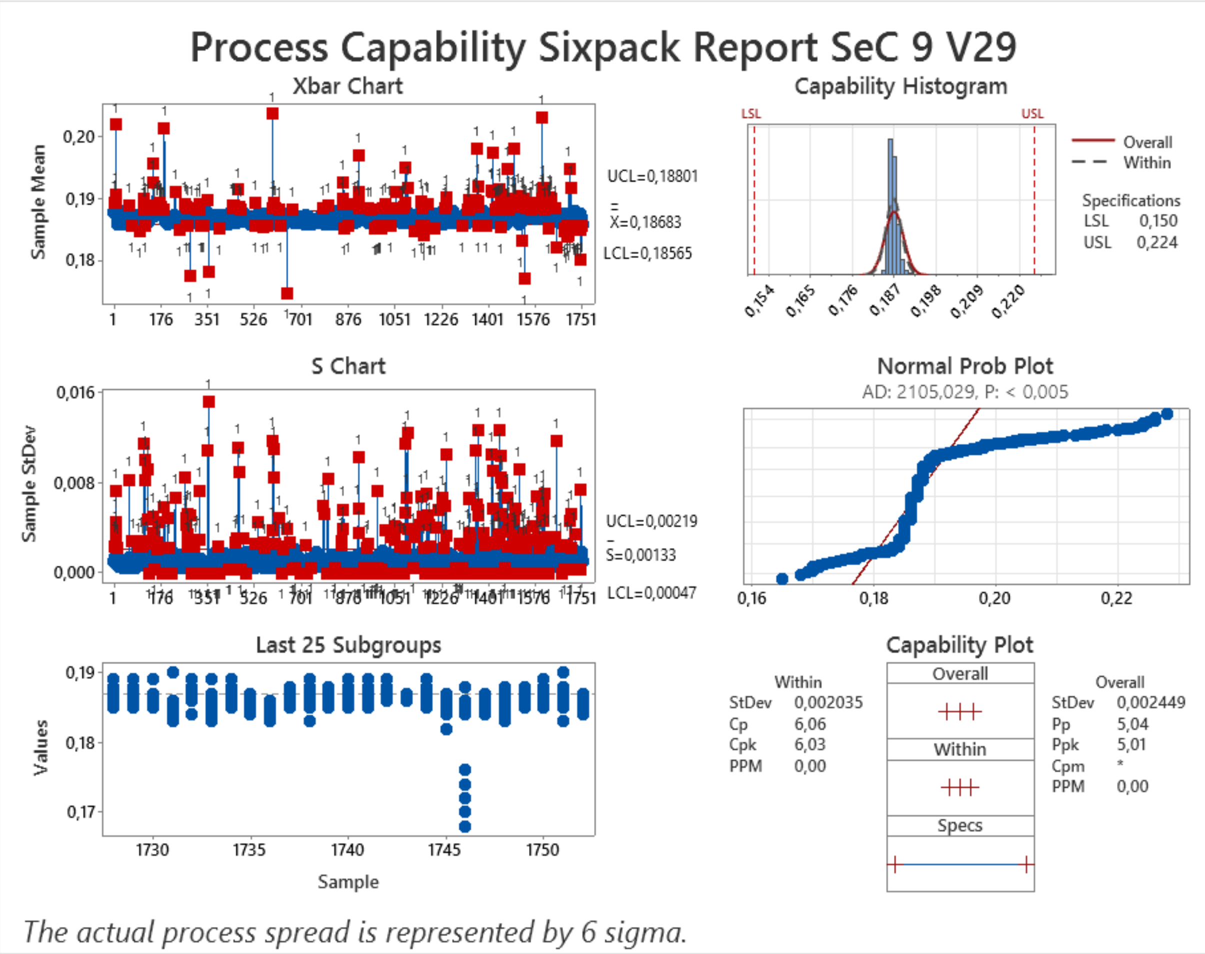



*Figure 20: SeC 9 V29 weeks 1-20 2022 1550 nm / ST002 Ø1.30/1.00 / 1752 Tube*

Finally, we examine the capability sixpack of the V30-Fibre of the 'SeC 9'. In Figure 21 and Figure 47 in Appendix A.4.2, we see the data for the attenuation of weeks 1 to 20 of 2022. The V30-Fibre is surrounded by a Soft Tube with an outside diameter of 1.15 mm and an inside diameter of 0.90 mm. For the $C_p$, $C_{pk}$, $P_p$and $P_{pk}$ we find the values 5.60, 5.15, 4.06 and 3.73, respectively. These values are extremely high, which means a sigma level of more than 6. Next to this, the average standard deviation is less than 0.002, the peak for the attenuation value is around 0.187 dB/km, and the defect rate is equal to 0.00 PPM.

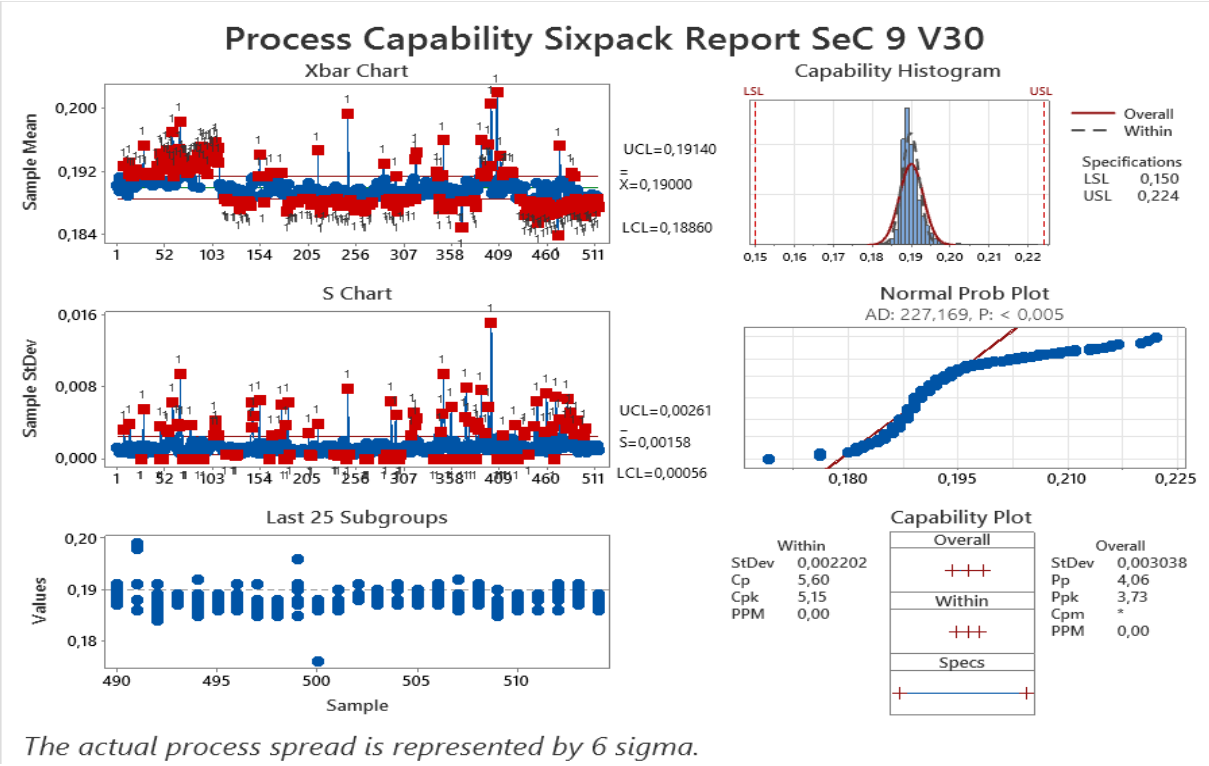



*Figure 21: SeC 9 V30 weeks 1-20 2022 1550 nm / ST004 Ø1.15/0.90 / 514 Tube*

### 4.3.3 Process capability average

Next to the process capability for the Xbar- and R-charts, we calculate the process capability for the I- and MR-chart. The I- and MR-charts focus on the average attenuation value of a tube, which excludes the outliers of a tube, and causes fewer Out-of-Control situations. However, we can still determine whether the system is Out-of-Control or not since all the fibres in a tube go through almost the same production process, only the first part of the process differs at the Unwinding unit (Section 2.2). So, for this reason, the I- and MR-charts are optional. Despite, the MSA on the means of the fibres could also not prove the reliability and validity of the MiniMAS, we do calculate the indices and control limits in order to provide a recommendation about which control chart to use for the implementation of SPC. For these studies, we use the same datasets as used for the capability studies in Sections 4.3.1 and 4.3.2. In Table 14, we calculate the control limits for I- and MR-charts. Furthermore, the table exhibits the $C_p$ and $P_{pk}$ values for the tubes. These indices are even larger than the indices for the individual fibres as calculated in Sections 4.3.1 and 4.3.2. All the indices are higher than 2.00 which indicates a Sigma level above six.

*Table 14: Control limits for I- and MR-charts including the capability indices (Attenuation at 1550 nm)*

| Type of fibre: | | N: | Mean | St. Dev. | I-Chart | | MR-Chart | | | Cp | Ppk |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | *LCL (dB/km)* | *UCL (dB/km)* | *LCL (dB/km)* | *MR (dB/km)* | *UCL (dB/km)* | | |
| *SeC 6* | Avg. V28 | 160 | 0.189 | 0.00186 | 0.185 | 0.192 | 0.0000 | 0.0012 | 0.0040 | 11.46 | 6.40 |
| | Avg. V29 | 1,213 | 0.187 | 0.00223 | 0.184 | 0.189 | 0.0000 | 0.0011 | 0.0035 | 13.09 | 5.47 |
| *SeC 9* | Avg. V29 | 1,752 | 0.187 | 0.00147 | 0.185 | 0.189 | 0.0000 | 0.0009 | 0.0023 | 16.14 | 8.26 |
| | Avg. V30 | 513 | 0.190 | 0.00217 | 0.186 | 0.194 | 0.0000 | 0.0015 | 0.0048 | 9.49 | 5.22 |

### 4.3.4 Preparation control limits

Sections 4.3.1 to 4.3.3 discussed several tubes on the Coating lines 'SeC 6' and 'SeC 9'. Although the high number of measurement errors, we notify that the tubes are performing really well according to the capability indices, mean, and standard deviation. However, there are still many Out-of-Control situations when we look at the number of data points that lie outside the control limits.

For the implementation of SPC, it is important to specify the control limits for the different types of fibre. Tables 15 and 16 summarize all the control limits for the Xbar- and R-charts and the I- and MR-charts which are determined for the control charts in Appendix A.4. We refer to Appendices A.4.1 and A.4.2 for further details on the analysis for the tubes produced on the 'SeC 6' and 'SeC 9', respectively. By comparing the graphs of the Xbar- and R-charts with the I- and MR-chart, we see fewer Out-of-Control situations for the I- and MR-charts. The main reason for this difference is due to the calculation of the control limits for the I- and MR-charts compared with the calculation of the control limits for the Xbar- and R-charts. Tables 15 and 16 show that for every fibre the upper limit of the I- and MR-charts is higher than for the Xbar- and R-charts. When the company faces too many Out-of-Control signals, it will be costly since all reels must be inspected for defects. Therefore, as a temporary solution, the company could decide to use the less sensitive I- and MR-charts. Using the I- and MR-charts it is still possible to control the attenuation on patterns with consecutive reels in the graphs. Furthermore, all the fibres within a tube go through the same production process because they will be bundled together at the start of the Coating line. So, in the case of an Out-of-Control situation, the tube has to show errors on multiple fibres. However, under the condition of a reliable and valid measurement system, the Xbar- and R-charts should always be the first choice of a company since these charts provide details about the quality of the tube at fibre level.

*Table 15: Control limits for the Xbar- and R-charts (Attenuation at 1550 nm)*

| Type of fibre: | | N: | Xbar-Chart | | R-Chart | | |
|---|---|---|---|---|---|---|---|
| | | | *LCL (dB/km)* | *UCL (dB/km)* | *LCL (dB/km)* | *R (dB/km)* | *LCL (dB/km)* |
| *SeC 6* | V28 | 160 | 0.186 | 0.191 | 0.0000 | 0.0074 | 0.0132 |
| | V29 | 1,213 | 0.185 | 0.188 | 0.0000 | 0.0039 | 0.0061 |
| *SeC 9* | V29 | 1,752 | 0.185 | 0.188 | 0.0000 | 0.0141 | 0.0243 |
| | V30 | 513 | 0.188 | 0.192 | 0.0000 | 0.0053 | 0.0091 |

*Table 16: Control limits for the I- and MR-chart (Attenuation at 1550 nm)*

| Type of fibre: | | N: | I-Chart | | MR-Chart | | |
|---|---|---|---|---|---|---|---|
| | | | *LCL (dB/km)* | *UCL (dB/km)* | *LCL (dB/km)* | *MR (dB/km)* | *UCL (dB/km)* |
| *SeC 6* | Avg. V28 | 160 | 0.185 | 0.192 | 0.0000 | 0.0012 | 0.0040 |
| | Avg. V29 | 1,213 | 0.184 | 0.189 | 0.0000 | 0.0011 | 0.0035 |
| *SeC 9* | Avg. V29 | 1,752 | 0.185 | 0.189 | 0.0000 | 0.0009 | 0.0023 |
| | Avg. V30 | 513 | 0.186 | 0.194 | 0.0000 | 0.0015 | 0.0048 |

## 4.4 Influence different types of fibre

For the implementation of SPC and the standardization of the control limits for different tubes, we investigate the root causes of the variation. Therefore, we conduct several hypothesis tests as explained in Section 3.4. With these hypothesis tests, we determine whether we can use the same control limits for different fibre types. For these tests, we consider three different kinds of fibres that are the V28- Fibre, V29-Fibre, and the V30-Fibre. Table 17 shows the descriptive characteristics of the samples. In this section, we provide only the outcomes of the hypothesis test. For further information about the calculation, we refer to Appendices A.6.1 and A.6.2.

*Table 17: Descriptive statistics*

| Sample | N | Mean | St.Dev | SE Mean |
|---|---|---|---|---|
| *SeC 6 V28* | 1,507 | 0.18816 | 0.00245 | 0.000063 |
| *SeC 6 V29* | 7,015 | 0.18687 | 0.00113 | 0.000013 |
| *SeC 9 V29* | 4,288 | 0.18687 | 0.00116 | 0.000018 |
| *SeC 9 V30* | 5,890 | 0.18967 | 0.00204 | 0.000027 |

### 4.4.1 Tubes 'SeC 6'

First, we investigate the statistical difference between the tubes on the 'SeC 6'. For this study we use tubes with V28- and V29-Fibres. From Table 17 with the descriptive statistics of these tubes, we see already a difference in mean and standard deviation. To check whether this hypothesis is statistically correct, we conduct a 2-sample t-test and a test for equal variances. First, the tubes are tested on different means. To test this, we conduct a two-sided test with a 5% level of significance ($\alpha = 0.05$). From the calculation in Appendix A.6.1, the p-value is equal to 0.000, so the null hypothesis must be rejected. We conclude that, statistically, we have enough evidence to assume that the mean for the two samples is different, at the 0.05 level of significance. Besides the t-test, we conduct a test for equal variances. This test is used to compare two variances with each other. Since the sample size is greater than 20, we use Bonett's test. From Appendix A.6.1, we find that the Bonett test calculates a p-value of 0.000. Since this value is lower than 0.05, we reject the null hypothesis and accept the alternative hypothesis. This means that statistically, there is a difference between the variances of the V28 and V29-Fibre of the 'SeC 6' at the 0.05 level of significance. After investigating these two tubes, we conclude that there is a difference between the mean and variance of the two tubes. Therefore, the fibres have an impact on the process, and we cannot use the same control limits for the two tubes on the 'SeC 6' at the implementation of SPC.

### 4.4.2 Tubes 'SeC 9'

Besides, the tubes produced on the 'SeC 6', we perform a 2-sample t-test for equal means and a test on equal variances on tubes produced on the 'SeC 9'. For this test, we consider the Soft Tubes with the V29- and V30-Fibres. From Appendix A.6.2, we find the p-value of 0.000. Therefore, we reject the null hypothesis, and accept the alternative hypothesis. Statistically, the mean for the two samples is different, at the 0.05 level of significance. The Bonett's test on equal variances provides a p-value of 0.000. Since this value is also lower than 0.05, we reject the null hypothesis and accept the alternative. So, as for the tubes produced on the 'SeC 6', we cannot standardize the control limits for the tubes produced on the 'SeC 9', since the mean and variance are statistically different.

## 4.5 Influence Coating line

Next to the different sorts of fibres, we also consider the several types of Coating lines at TKF. Since the Coating lines are not the same, we have to determine whether we can use the same control limits. To measure the influence of a Coating line, we use two samples. The first sample is the V29-Fibre produced on the 'SeC 6' and the second is the same fibre produced on the 'SeC 9'. In Table 18, we find the descriptive statistics of these two samples. For the 'SeC 6', the sample size is equal to 7,015 and for the 'SeC 9' 4,288. When we look at the mean of the samples, we already see that there is no difference between the fibres. For the calculation of the tests, we refer to Appendix A.6.3.

*Table 18: Descriptive statistics*

| Sample | N | Mean | St.Dev | SE Mean |
|---|---|---|---|---|
| *SeC 6 V29* | 7,015 | 0.18687 | 0.00113 | 0.000014 |
| *SeC 9 V29* | 4,288 | 0.18687 | 0.00116 | 0.000021 |

In order to know, whether it is possible to use the same control limits on the two Coating lines, we compare the mean and the standard deviation values from Table 18. For the implementation of SPC on the Coating lines at TKF a control limit of three decimals is necessary. At the values from the table, we see that the mean and the standard deviation of the two samples are equal. However, for extra confirmation, we also conduct the 2-sample t-test with a 5% significance level ($\alpha = 0.05$). Appendix A.6.3 provides the p-value of 0.061. This means that we fail to reject the null hypothesis. Statistically, we do not have enough evidence to assume a different mean for the two samples, at the 0.05 level of significance. Besides the t-test, we conduct a test for equal variances. For Bonett's test, we find a p-value of 0.134 in Appendix A.6.3. Since this value is higher than 0.05, we cannot reject the null hypothesis. So, there is no significant difference between the V29-Fibre of the 'SeC 6' at the 0.05 level of significance. According to these tests, we conclude that there is not a significant difference between the tubes produced on the 'SeC 6' and the 'SeC 9'. This result means that the two different Coating lines of TKF do not directly influence the attenuation value of these tubes. However, this study does not prove that the other Coating lines at TKF cannot influence the attenuation value of a tube.

## 4.6 Conclusion

In Section 4.1.1, we conducted several MSAs on the MiniMAS at TKF. Nevertheless, none of them could prove the reliability and validity of the measurement system. With the two hypothesis tests on the mean and variances for different positions on the MiniMAS, we cannot assume a significant difference. For this reason, we assume that the position where the fibre is measured does not influence the measured value. Next to this, we determined the statistical characteristics of different fibre types. We provided the mean and variance for the fibres which are used in this research. Furthermore, an Anderson-Darling test is conducted to find a proper distribution that fits the dataset. However, none of the fourteen distributions fits any dataset. Therefore, we assume normality since the normal distribution has the most corresponding curve and statistical characteristics. Moreover, the normal distribution is a widely used distribution in the literature regarding similar studies. Next to this, we determined the capability of the Coating lines and investigated whether it is possible to standardize the control limits for different types of Coating lines and fibre. For the capability, we observed that the $C_p$ and $P_{pk}$ indices are high, with a sigma level above six. This means that the number of failures per million parts is less than 3.4. The hypothesis tests in this chapter show that we cannot prove a significant difference between the mean and variance for the two Coating lines. However, the t-test and test for equal variances show a significant difference between the fibres. For that reason, the control limits for different fibres have to be calculated on their own. In the final part, we determine the root causes of the measurement errors at different levels. Here, we find several causes for errors. For instance, the type of material, generally the V29-Fibre produces fewer errors than the other fibres. The degree in education is also an influencing factor since we come across a lot of failures due to human beings.

# 5. Improving the production process

In this chapter, we discuss the Improve phase of the research. Here, we elaborate on the following research questions identified by RQ5 and RQ6:

RQ 5: "Which implementations improve the process performance on the Coating line?"

RQ6: "How will the improvements be sustained after the project closure?"

We divide this problem into the following sub-questions:

- "What are possible improvements regarding the measurement of attenuation of the fibres?"
- "What is the potential process capability on the Coating line?"
- "Which software improvements are required for the implementation of SPC?"
- "How should the improvements be measured and controlled on the Coating line?"

Section 5.1 describes the measurement of the attenuation. Specifically, we discuss the possible improvement to the measurement system. Then, Section 5.2 provides the calculation of the potential capability of the process, and in Section 5.3 the contribution of SPC to the process is discussed. In Section 5.4, we determine software requirements for the implementation of SPC. Finally, Section 5.5 determines how to control the process and explains how to preserve the improvements after project closure.

## 5.1 Measurement improvements

In Section 4.1, we discussed the issues regarding the current way of measuring. The MSA demonstrated that the current measurement system is not reliable. Furthermore, the study of the measurement system indicates an average FTR of correct measurement of 81.47%. To come up with possible solutions concerning the measurement, we use the Ishikawa theory as an inspiration source. The Ishikawa theory is a commonly used theory to collect possible causes for a certain effects (Górny, 2017). For this research, we use the six main elements of the Ishikawa theory to determine possible improvements. The elements consist of Measurement, Machine, Man, Environment, Method, and Material. First, the Measurement and Method. As mentioned earlier, TKF has two different types of measuring systems the manual MAS and the MiniMAS. During this research, we could not prove the reliability and validity of the MiniMAS. We found different causes, for instance, the capability of the operator to work with the measurement system and the unfavourable samples for the MSA. The range of these samples was between 0.185 dB/km and 0.191 dB/km, but the actual production range is between 0.185 dB/km and 0.200 dB/km. A sample group that represents better the range of the production is more suitable to distinguish the Discrimination and to determine the variation caused by the operators and the measurement system. Next to this, the unreliability of the MiniMAS is also caused by the sensitivity of the system that cannot be influenced by the operators since the MiniMAS automatically measures the fibres. In the short-term, we deem a new measurement system as unnecessary, since the measurement system provides a good identification of whether the reel should be approved or disapproved. Nevertheless, in the long-term, a new MSA using samples with a wider range of attenuation and well-trained operators should prove the reliability of the measurement system. In case it is not possible to prove the reliability of the system, we recommend investigating whether another measurement system would be more suitable. For the measurement machine, we recommend maintenance on half yearly basis because, as mentioned in Section 4.1.3, one MiniMAS shown some failures regarding the position of measuring that can have a major impact on the fibre measurements, e.g., the MiniMAS measured some fibres at an incorrect position due to an issue with the mechanism of the device.

To improve the workspace, the company should introduce the 5S theory. The purpose of the 5S theory is to realize an organized workspace on five different points which are Sort, Straighten, Shine, Standardize and Sustain (Theisens, 2018). Partially, the company has already introduced the 5S theory within the company since the tools and materials of the production line have a fixed place. To implement this system at the measurement stations, it is necessary that these items and tools also get a permanent location with fixed trays and based on the frequency of use. Furthermore, it is important to keep the workplace clean. Therefore, it should be clear for the operators to know what, when, and by whom the workplace should be cleaned. We recommend that the measurement station should be clear at the end of a shift. So, at the end of a working day for an operator. It should only take 5 minutes to put every item in the right place and this ensures that the desk is clean. When an item is missing the operators should report that. Furthermore, it is recommended to hang a list of materials at the stations, so the operators can easily see which tools should be present.

Finally, we consider the training of the staff regarding the measurement of the fibre. The staff needs extra training to work with the MiniMAS. Currently, the training mainly focuses on the manual MAS. However, the MiniMAS is an important measurement system to improve the efficiency of the production process because the operator prepares the fibres of the tube at once. Then, the system goes automatically through all the fibres. The manual MAS measures the fibres separately. Here, the operator needs to prepare the fibres one by one. Nevertheless, the measurement with the MiniMAS needs more accuracy and is really sensitive. Therefore, we recommend providing extra training materials for the operators and including the MiniMAS in the training program of TKF. Adding this to the training program will save a significant amount of time, stress, and measurement errors, which also improves the specifications of the fibre optics cables by preventing common mistakes, such as the mistakes described in Section 4.1.3.

## 5.2 Potential process capability

In this section, we recalculate the control limits without using the data of the incorrect measurement. After we calculated the process capability of the Coating lines in Section 4.3, we knew how the current process performance of the coating process with an unreliable data. Now, in this section, we calculate the performance without invalid data.

In Section 5.2.1, we conduct a capability study on the V28- and V29-Fibres produced on the Coating line 'SeC 6' and in Section 5.2.2, we conduct a capability study on the V29- and V30-Fibres produced on the Coating line 'SeC 9'. Section 5.2.3 provides the process capability for the same fibres on average. Finally, in Section 5.2.4, we provide an overview of all the control limits we have calculated.

### 5.2.1 SeC 6 Process capability

In Section 4.1.1, we mentioned that we cannot prove the reliability of the MiniMAS following the acceptance standards of the AIAG (McNeese, 2018). In order to calculate the potential of the production process, we only use the attenuation values that are measured by manual MAS. Moreover, since we are not able to solve the problems with the measurement errors in the short-term, we exclude the measurement errors from the data set. First, we start with a calculation of the process capability of the V28-Fibre measured on the manual MAS and we exclude the measurement errors. Then, we do the same for the V29-Fibre.

In Figure 22, we find the capability sixpack of the tube with V28-Fibres produced at the Coating line 'SeC 6'. When we take a look at the figure we find a $C_p$ of 5.15, a $C_{pk}$ of 4.98, a $P_p$ of 4.76 and a $P_{pk}$ of 4.61. This mean that the Sigma level is above six since the specification width for capability is larger than 6 Sigma and for the performance it is larger than twelve Sigma. Furthermore, these capability and performance indices are even higher as the indices of the V28-Fibres of the 'SeC 6' in Section 4.3.1. So, there is potential to perform even better than the current system is doing. Next to this, overall, the process looks stable although there are some drifts in the process. The standard deviation is less than 0.003, besides, we observe a high peak in the histogram at the attenuation value of 0.187 dB/km.

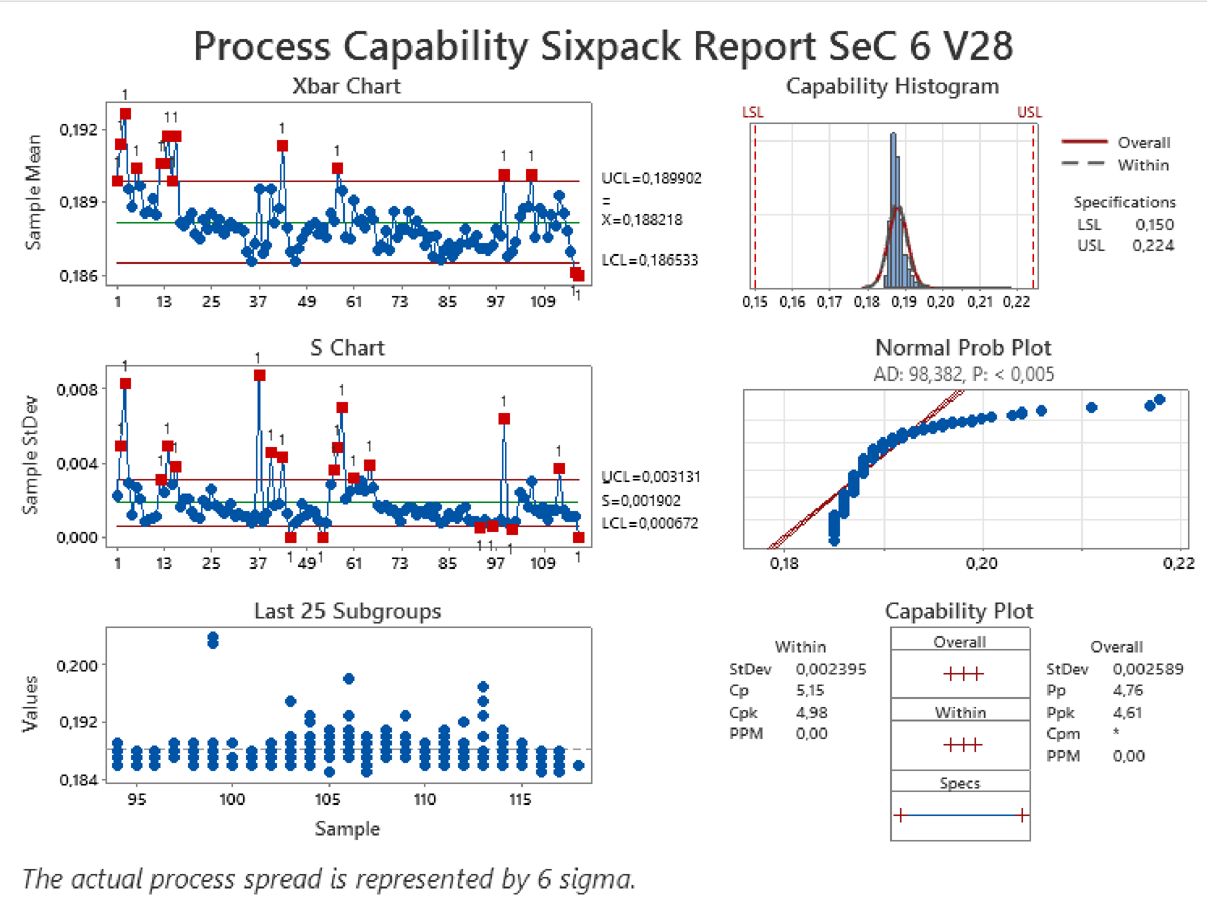



Figure 22: SeC 6 V28 weeks 1-20 2022 1550 nm / ST002 Ø1.30/1.00 / Tube

Figure 23 displays the capability sixpack of the tube with V29-Fibres produced at the Coating line 'SeC 6'. In this figure, we find a $C_p$ of 13.11, a $C_{pk}$ of 13.06, a $P_p$ of 11.35 and a $P_{pk}$ of 11.31, these values are also higher than the indices of Section 4.3.1 and indicate a Sigma level above six. The reason for these high indices is, again, the generous specification limits that are set to wide. With the implementation of SPC, we also calculate new control limits which result in more realistic capability values. We provide these control limits in Section 5.3. Next to this, the Xbar-chart in Figure 23 shows a drift at sample 449. Overall, the process looks very stable. For the lower control limit, we calculate a value of 0.186 and for the upper limit 0.188. The average standard deviation is less than 0.0009 besides, there is a high peak at the attenuation value of 0.187 dB/km.

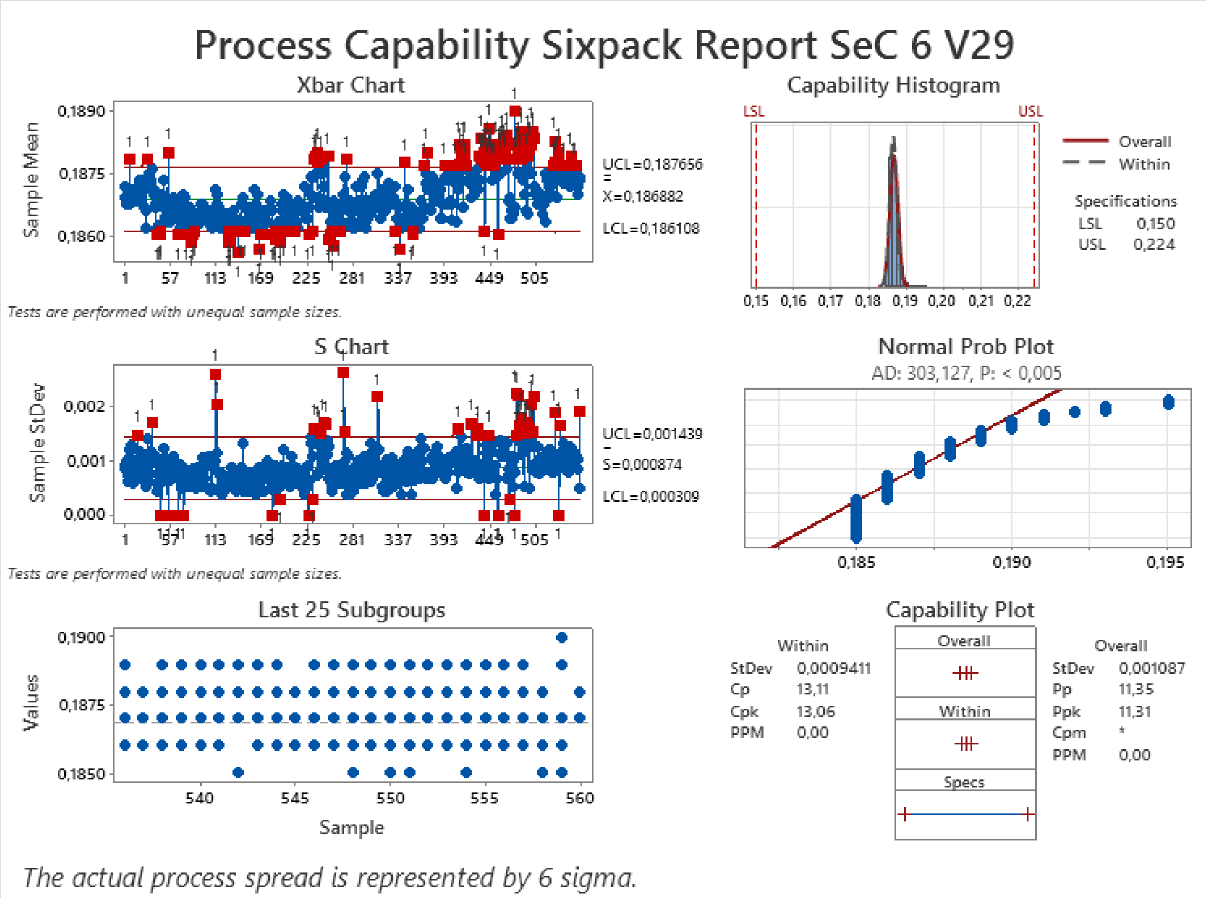
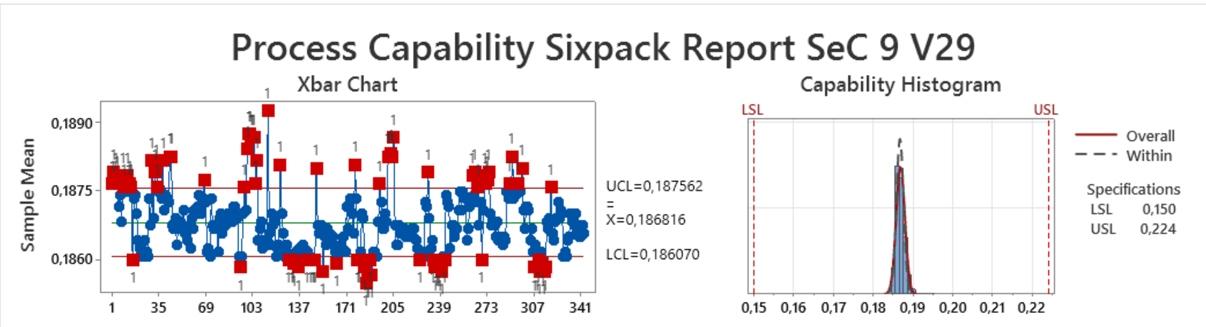


*Figure 23: SeC 6 V28 weeks 1-20 2022 1550 nm / ST002 Ø1.30/1.00 / Tube*

## 5.2.2 SeC 9 Process capability

In this section, we do the same as in Section 5.2.1, we calculate the process capability of the tubes of the manual MAS and exclude the measurement errors. However, we study the V29 and V30-Fibres for the 'SeC 9'.

For the process capability sixpack of the tube with V29-Fibres produced on the 'SeC 9', we look at Figure 24. This figure provides the capability indices for attenuation a $C_p$ of 13.58 a $C_{pk}$ of 13.51, a $P_p$ 11.15 and $P_{pk}$ of 11.09. As for the other fibres, these values are extremely high and higher than the capability indices calculated in Section 4.3.2. Overall, the process looks stable with slightly higher shifts than the V29 of the 'SeC 6'. However, this difference could be the result of a larger sample size. The lower control limit of this tube is equal to 0.186 and an upper limit of 0.188. The average standard deviation is a bit lower, 0.0008. Besides, also for this fibre, we observe a peak at the attenuation value of 0.187 dB/km.



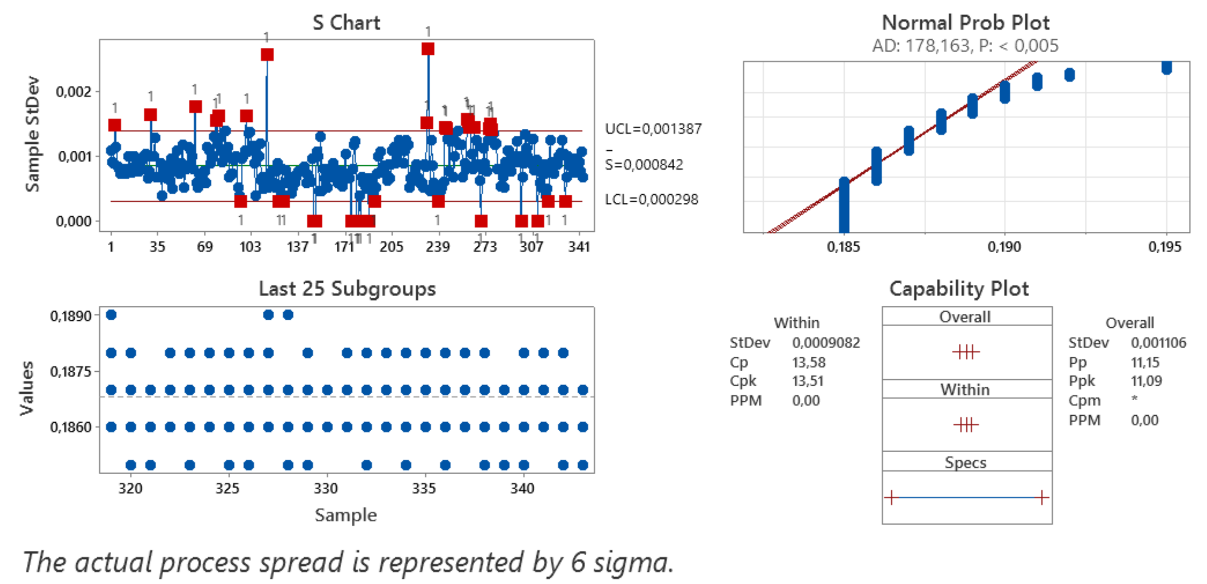



*Figure 24: SeC 9 V29 weeks 1-20 2022 1550 nm / ST002 Ø1.30/1.00 / Tube*

In Figure 25, we find the capability sixpack of the tube with V30-Fibres. This figure provides us with a $C_p$ of 11.07, a $C_{pk}$ of 10.50, a $P_p$ of 8.36 and a $P_{pk}$ of 7.93. This means that we also have a Sigma level above 6 since the specification width for the capability is larger than 6 Sigma and larger than 12 Sigma for the performance. Next to this, the process shows some small drifts, e.g., at the first couple of samples and the final 10 samples. Overall, the process looks stable with an average standard deviation of approximately 0.001 and a high peak at the attenuation value of 0.187 dB/km.

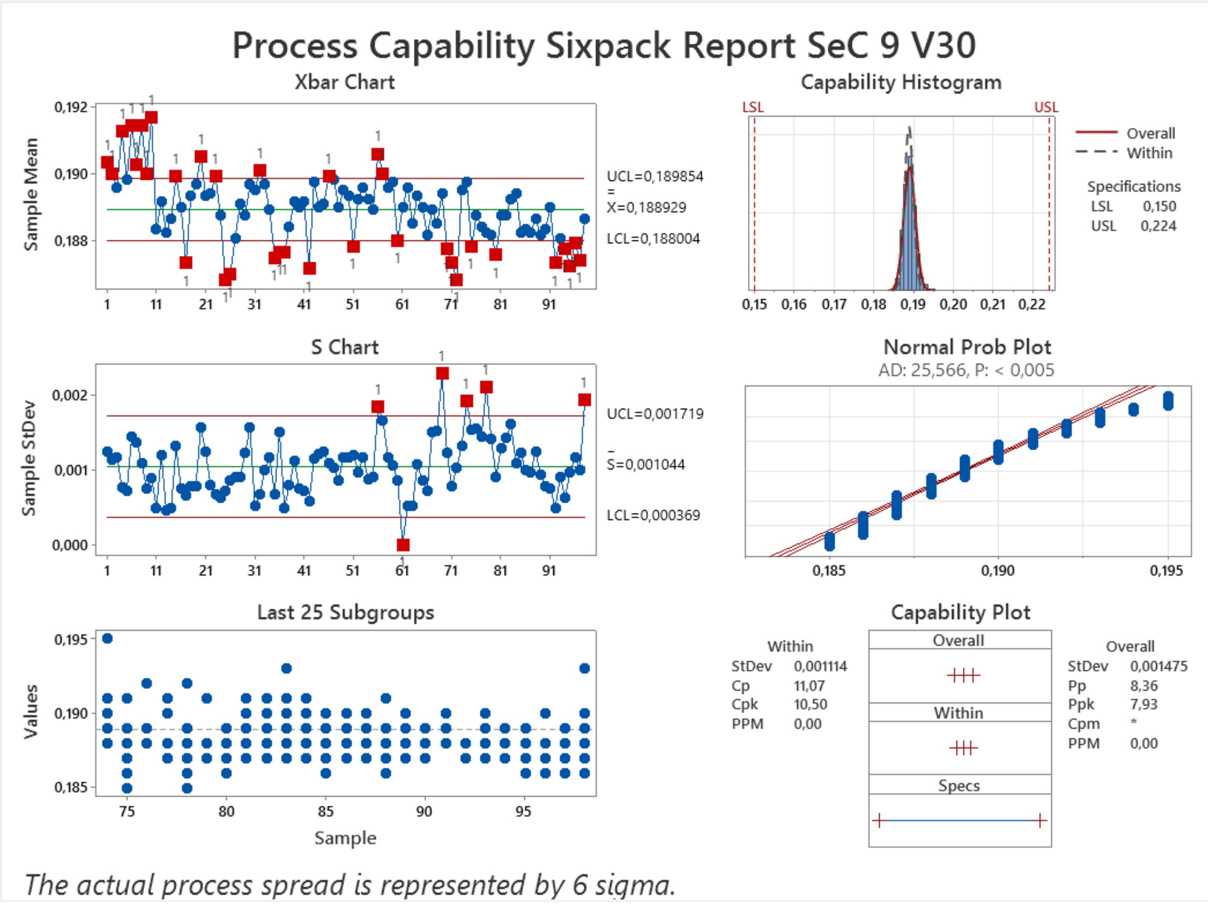



*Figure 25: SeC 9 V30 weeks 1-20 2022 1550 nm / ST004 Ø1.15/0.90 / Tube*

### 5.2.3 Process capability average

As in Section 4.3.4, we calculated the control limits for the I- and MR-chart. Calculating these control limits helps us to understand which control limits and control charts are most applicable to use for the implementation of SPC on the Coating lines. In Table 19, we find the $C_p$and $P_{pk}$indices of datasets without the incorrect measurement of the 'SeC 6' and 'SeC 9'. Again, for these tubes, the capability indices are extremely high and even higher as for the indices of Section 4.3.3. An advantage of the Xbar- and R-charts is that these charts provide information about the tube at fibre level. The I- and MR-charts provides only information about the average of the tube which makes it difficult to analyse the increase in attenuation of fibre during the Coating line with respect to the Colour line. An advantage of the I- and MR-charts is that they offer fewer Out-of-Control situations. Since we take the average of a tube, we do not observe the extreme values of a tube which lies outside the spectrum. Next to this, the control limits for the I-chart are a slightly higher. By combining these two elements, we find fewer Out-of-Control. However, this advantage is more extensive when the measurement system is not correctly calibrated and operated. As we explain on the next page, the overall process variation consists of two parts: process and measurement variation. In case of a higher measurement variation (the measurement procedure is less reliable), even the overall variation will be higher. This means that the number Out-of-Controls of the Xbar- and R-charts increases more than the number of Out-of-controls of the I- and MR-charts since these will be neutralized by taking the average of the tube.

*Table 19: Control limits for I- and MR-charts including the capability indices (Attenuation at 1550 nm)*

| Type of fibre: | | N: | Mean | St. Dev. | I-Chart | | MR-Chart | | | Cp | Ppk |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | *LCL (dB/km)* | *UCL (dB/km)* | *LCL (dB/km)* | *MR (dB/km)* | *UCL (dB/km)* | | |
| *SeC 6* | Avg. V28 | 111 | 0.188 | 0.00120 | 0.186 | 0.191 | 0.0000 | 0.0008 | 0.0028 | 16.51 | 9.91 |
| | Avg. V29 | 560 | 0.187 | 0.00061 | 0.186 | 0.188 | 0.0000 | 0.0004 | 0.0012 | 37.67 | 20.22 |
| *SeC 9* | Avg. V29 | 343 | 0.187 | 0.00069 | 0.186 | 0.188 | 0.0000 | 0.0004 | 0.0014 | 31.53 | 17.82 |
| | Avg. V30 | 98 | 0.189 | 0.0010 | 0.186 | 0.191 | 0.0000 | 0.0009 | 0.0031 | 14.87 | 11.42 |

## 5.3 Implementation SPC

In this section, we determine the control limits for the SPC software and discuss why it is essential to implement SPC on the Coating lines at TKF. For the implementation of SPC on the Coating line, it is important to use proper control limits. Therefore, we have calculated the control limits for different combinations of tubes and fibres. We have to be careful with the determination of the control limits since a too-small range will lead to a high percentage of Out-of-Control situations. In this case, a reel has to be placed in quarantine for inspection. A high percentage of Out-of-Controls is very costly and time-wasting. Furthermore, we calculate the standard deviation caused by the MiniMAS measurement system. Since we could not prove the reliability and validity, we determine an extra margin of error for the lower control limits in order to know which part of the variation is caused by the MiniMAS.

In Sections 4.3 and 5.2, we discussed the control limits for different types of tubes and Coating lines. After the hypothesis test in Section 4.5, we find that there is no statistical evidence against the similarity of the control limits for different Coating lines. For that reason, we use the same control limits for the matching tubes in this research. In Table 20 and Table 21, we define all the control limits for the implementation of SPC at the Coating lines. For the lower control limit of the Xbar- and I-charts, we set the absolute attenuation at 0.185 dB/km because this value is the most optimal possible result. The attenuation of 0.185 dB/km can be seen as an asymptote, this means that on the condition that the measurement is correct, it is not possible to obtain a lower value than this number due to the characteristics of the fibres. In Section 4.1.1 we discovered that the MiniMAS measurement system cannot meet the acceptance standards followed by the AIAG. Therefore, we have to implement a margin of error for this measurement system. We determine this margin by calculating the variation caused by the measurement system and subtract this from the lower control limit. The overall variation of the process consists of two parts, the process variation and measurement system variation. Since we take a fixed value for the lower control, the measurement system variation is not included at the determination of the control limits. For this reason, we only subtract the outcome of this variation from the lower control limit. We use the following formula for the calculation of the variation (standard deviation) of the measurement system:

$$\delta_{Measurement\ system} = \sqrt{percentage\ R\&R\ study\ variation\ \ * \delta^2_{observed}}$$

*Equation 5: Standard deviation measurement station*

For the percentage of R&R Study variation, we take the value that we have calculated in Section 4.1.1 shown in Table 8, which is equal to 68.06%. $\delta^2_{observed}$ Means the total process variation which consists of the process variation and measurement variation. The value for $\delta^2_{observed}$ is equal to the square of the standard deviation exhibited in Appendix A.2. In this appendix, we find an average standard deviation for the different fibre types equal to 0.002895. Using this value, we find a $\delta_{Measurement\ system}$ of 0.00238 which is approximately 0.002. Therefore, we have to keep in mind that the system could measure a value of 0.183 dB/km, due to inaccuracies with the measurement system in the current situation. For this reason, it is convenient to implement this margin. Otherwise, the number of Out-of-Controls increases unnecessary. Next to this, we set the lower limit of the MR-chart at zero since the company strives for consistency which means that the lower limit has to be as low as possible. For that reason, the best possible option for the MR value is equal to zero.

When we inspect the control limits in the tables below, we see that there is only a small difference between the Xbar-chart and the I-chart data from the manual MAS system. So, it seems that it does not matter which control chart to use regarding the control limits. Moreover, if there is a difference between these chart, then for nearly every control limit, the control limit of the I-chart is 0.001 wider. As mentioned earlier, the preference of the company is an Xbar- and R-charts because these charts provide us more detail about the fibres. However, as discussed in Sections 4.3.3 and 5.2.3, we also investigated the I- and MR-charts. Tables 20 and 21 give two different control limits for each sample. The first row shows the control limits for the current performance, including the measurement errors. In each second row, all the errors regarding the measurement are excluded and only data from the manual MAS measurement system is considered. These rows show the potential control limits for the process under the condition of a reliable and valid measurement system.

Next to this, the final two columns of Table 20 demonstrate the number of Out-of-Control situations. With the normal go, no go, principle which TKF is currently using, these Out-of-Controls are not detected. SPC contributes to finding patterns between consecutive reels of tubes as shown in the capability sixpacks in Sections 4.3 and 5.2, and in more detail in the graphs of Appendices A.4 and A.5. Furthermore, using SPC, the managers are able to intervene immediately and discover the root causes of the Out-of-Control situation. This way, it is possible to improve the FTR percentage of the "All data" row since these percentages are low. Overall, the FTR percentages of "Correct measurement from manual MAS" are higher. Nevertheless, there is still a lot of space for improvement in these datasets. With the implementation of SPC in the future, it should be possible to reduce the process variation of the Coating lines even further in order to decrease the number of Out-of-Control situations. This way, the company gets a better understanding of the root causes of the process variation since SPC helps to constantly detect drifts and shifts at the attenuation value of the fibres.

*Table 20: Recommend control limits for Xbar- and R-chart (Attenuation at 1550 nm)*

| Capability study | | Data | N: | Xbar-Chart | | R-Chart | | | Nr. OoC | FTR |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | *LCL (dB/km)* | *UCL (dB/km)* | *LCL (dB/km)* | *R (dB/km)* | *UCL (dB/km)* | | |
| *SeC 6* | ST002 / V28 | All data | 160 | 0.183 | 0.191 | 0.0000 | 0.0074 | 0.013 | 36 | 77.50% |
| | | Correct measurement from manual MAS | 111 | 0.185 | 0.190 | 0.0000 | 0.0062 | 0.0106 | 18 | 83.79% |
| | ST002 / V29 | All data | 1,213 | 0.183 | 0.189 | 0.0000 | 0.0027 | 0.0061 | 266 | 78.07% |
| | | Correct measurement from manual MAS | 559 | 0.185 | 0.188 | 0.0000 | 0.0027 | 0.0047 | 95 | 83.01% |
| *SeC 9* | ST002 / V29 | All data | 1,752 | 0.183 | 0.188 | 0.0000 | 0.0141 | 0.0243 | 277 | 84.19% |
| | | Correct measurement from manual MAS | 343 | 0.185 | 0.188 | 0.0000 | 0.0026 | 0.0045 | 57 | 83.09% |
| | ST004 / V30 | All data | 513 | 0.183 | 0.191 | 0.0000 | 0.0053 | 0.0091 | 136 | 73.48% |
| | | Correct measurement from manual MAS | 98 | 0.185 | 0.190 | 0.0000 | 0.0034 | 0.0059 | 25 | 74.49% |

*Table 21: Recommend control limits for I- and MR-chart (Attenuation at 1550 nm)*

| Capability study | | Data | N: | I-Chart | | MR-Chart | | |
|---|---|---|---|---|---|---|---|---|
| | | | | *LCL (dB/km)* | *UCL (dB/km)* | *LCL (dB/km)* | *MR (dB/km)* | *UCL (dB/km)* |
| *SeC 6* | ST002 / V28 | All data Avg. | 160 | 0.183 | 0.192 | 0.0000 | 0.0012 | 0.0040 |
| | | Correct measurements from manual MAS Avg. | 111 | 0.185 | 0.191 | 0.0000 | 0.0008 | 0.0028 |
| | ST002 / V29 | All data Avg. | 1,213 | 0.183 | 0.189 | 0.0000 | 0.0011 | 0.0035 |
| | | Correct measurements from manual MAS Avg. | 559 | 0.185 | 0.188 | 0.0000 | 0.0004 | 0.0012 |
| *SeC 9* | ST002 / V29 | All data Avg. | 1,752 | 0.183 | 0.189 | 0.0000 | 0.0009 | 0.0023 |
| | | Correct measurements from manual MAS Avg. | 343 | 0.185 | 0.188 | 0.0000 | 0.0004 | 0.0014 |
| | ST004 / V30 | All data Avg. | 513 | 0.183 | 0.194 | 0.0000 | 0.0015 | 0.0048 |
| | | Correct measurements from manual MAS Avg. | 98 | 0.185 | 0.191 | 0.0000 | 0.0009 | 0.0031 |

On the other hand, instead of implementing SPC over the entire production process, the company could decide to measure the fibres once for final approval and discard the entire measurement procedure after every production step. In this situation, the fibres are only measured by well-trained people since the measurement is the main activity at the final inspection department. Furthermore, this alternative will exclude the measurement errors caused by operators who are less educated regarding the measurement procedure. Furthermore, in Sections 4.3 and 5.2, we demonstrate that the production process is rather stable, has extremely high capability indices, and almost none of the fibres has an attenuation value above or below the specification limits defined by the research and development department.

Although the exclusion of the intermediate measurements has several benefits, it remains very costly if a cable has to be disapproved after the final inspection due to too high attenuation of a fibre. Moreover, the measurement systems are already purchased, the tools are available for the operators, and the measurement has only a marginal influence on the changeover time of the process. Apart from this, we observed many Out-of-Control situations in the control charts of the capability studies. This indicates that there is also a lot of space to improve and get the system In-Control. Furthermore, the implementation of SPC at TKF is in the spirit of the company. TKF attaches great importance to real-time process control. By implementing SPC, the company has the ability to discover patterns and constantly improve and monitor the production process. Furthermore, it enables us to investigate the production history of a fibre optics cable when a customer encounters issues with the cable. Therefore, we have decided to keep the intermediate measurements and improve the measurement procedure.

## 5.4 Dashboard SPC Software

As mentioned at the beginning of the report, this research is follow-up on a study regarding the implementation of a statistical analysis procedure in the production process at TKF. During Phase-1, the focus was on a draft version of the implementation of SPC for monitoring the Colour lines. Then, in Phase-2, we worked on the improvements and implementation of the software at the Colour lines. Now, in Phase-3, the purpose is to expand the current software to the Coating lines by making adaptions to the current system. Furthermore, a programme of requirements is necessary for the design of the dashboard. One of the key points for the implementation of the software is to obtain user-friendly software that is suitable for the operators and managers and pleasant to work with. Since there is already software running on the Colour lines, we can further develop the current system and make it applicable on the Coating lines. Figure 26 exhibits the current dashboard and Figure 27 provides a draft of the updated version of the dashboard. In the following section, we discuss the requirements for the software on three different elements, layout, visualization of data and functionality.

**Layout**

For the layout of the dashboard, no major changes are necessary compared with the software of the Colour line. Only at the top of the dashboard at Point 1 in Figure 27 are a few changes required. The header of the dashboard is currently based on the Colour lines. This has to be changed to make it also applicable for the Coating lines. Furthermore, on the dashboard, we find 'Onbekend' (Unknown) or the name of the Colour line. This has to be changed to 'Alle lijnen' (All production lines) or the name of a specific Coating line. Finally, to make the software applicable for the Coating line, on the top left 'VezelType' (type of fibre) has to be changed to 'TubeType'.

**Visualization of data**

At Point 2, the dashboard must show the Xbar- and R-charts or the I- and MR-charts of the absolute value of the attenuation of a tube. At Point 3, the future plan for the dashboard is to show also the Xbar- and R-charts or the I- and MR-charts of the increase in attenuation of a tube. However, it is currently not possible since the Enterprise Resource Planning (ERP) system of the company is undergoing an overhaul at the moment. When this system is active throughout the company, an extended study regarding the increase in attenuation is necessary to determine the control limits for these charts. Furthermore, at Point 4, we insert an extra button ‘Vezel waarden’ (Information at fibre level) next to the ‘SPC Tabel’ (SPC Table). The ‘SPC Tabel’ exhibits all the information on the control charts that is on the dashboard. However, the ‘Vezel waarden’ table shows extended information about the tube at fibre level. For instance, when we consider a tube with 12 fibres, the ‘SPC Tabel’ shows the production number, date, time, Xbar-value, R-value, etc., but the ‘Vezel waarden’ table provides besides the common production information, the absolute attenuation value, and the increase in attenuation value of all the 12 fibres.

**Functionality**

Regarding the functionality, on the right side of Figure 27, it is possible to change settings for the dashboard. On the top right at Point 5, the type of fibre has to be changed to the type of tube. Furthermore, since there are more kinds of tubes than fibres, it will be easier to implement a drop-down menu. Finally, at Point 6, it should be possible for the operators or managers to input the number of data points they want to see.

**Communication**

Last, it is important that the software system is able to communicate with the different measurement systems in order to exchange the data. The ERP system is already developed for the company. However, it is still not integrated into the processes. In the current situation, the SPC software is communicating through an internal database. For further development, we recommend integrating the ERP system with the measurement systems, in order to make the SPC software functional for use.

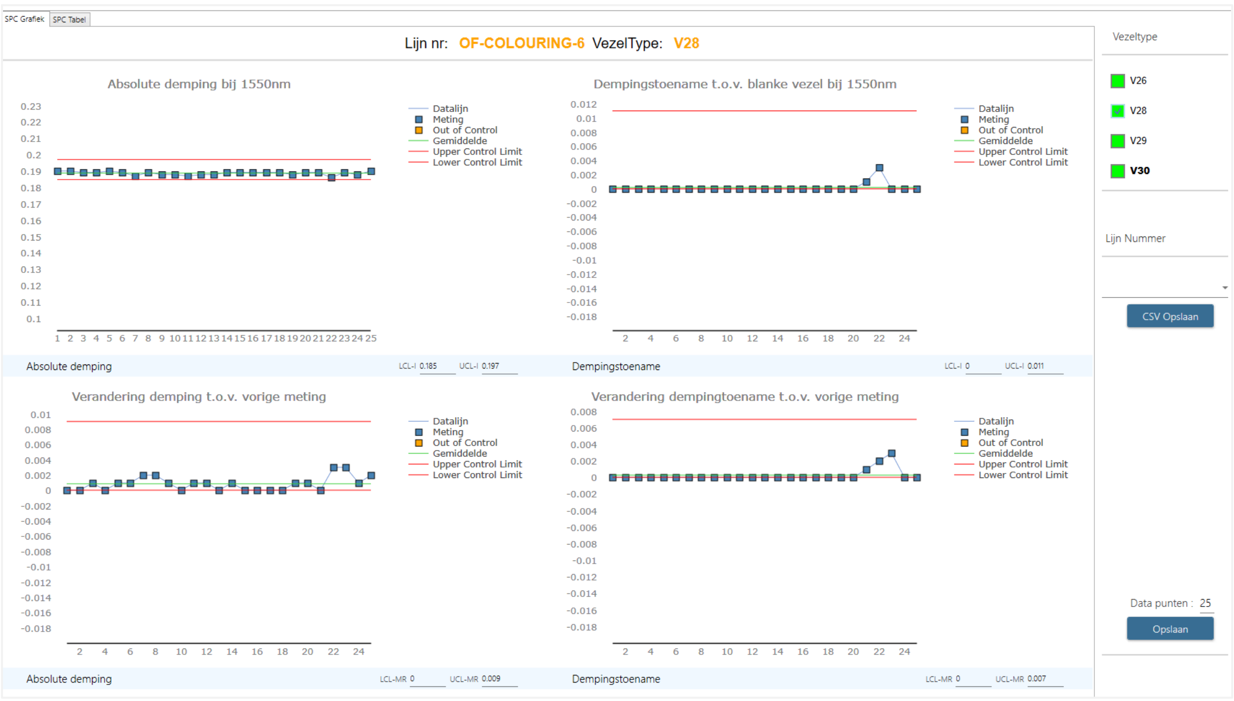



*Figure 26: Current dashboard of the SPC-software for the Colour line*

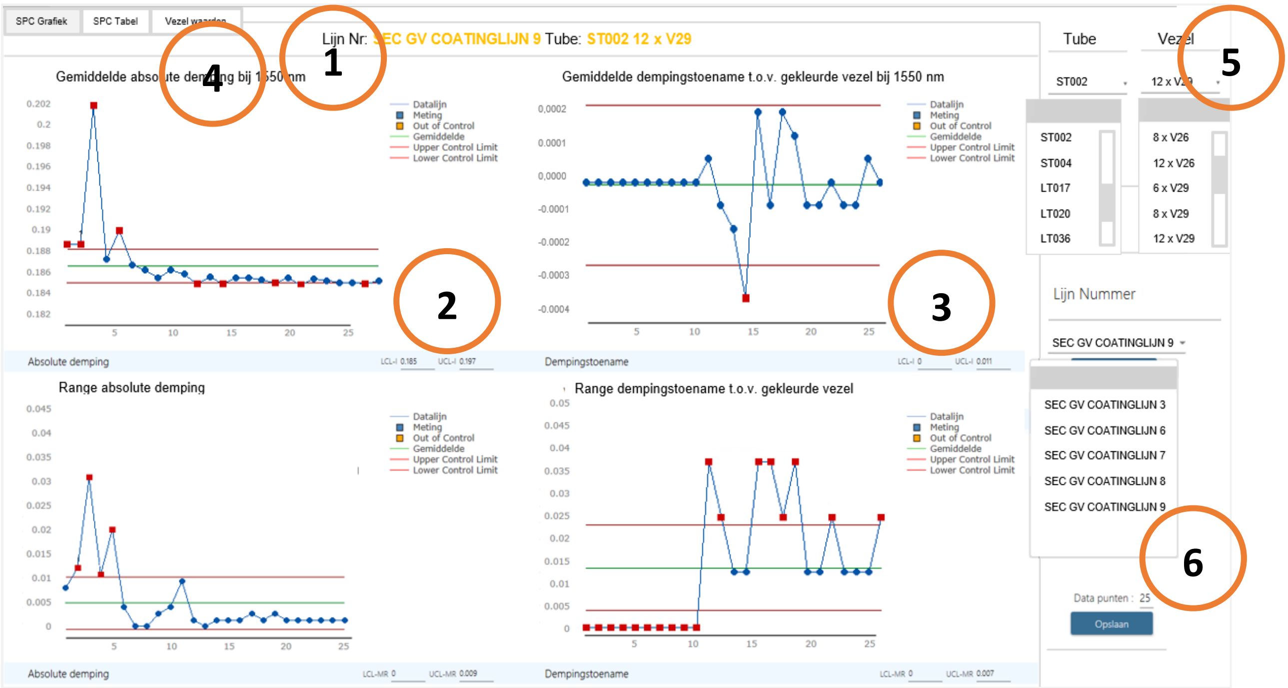


*Figure 27: New dashboard of the SPC-software for the Coating line*

In Table 22, we provide a programme of requirements for the new software. The purpose of the software is to create two types of user accounts, one for the operators and the other for the managers. In Table 22, we provide all the requirements that are necessary for the user in order to be able to monitor and control the production process of fibre optics cable.

*Table 22: SPC software requirements*

| Categories | User | |
|---|---|---|
| | *Operator (Default)* | *Specialist +* |
| *Xbar-R-Charts Absolute* | Xbar-chart absolute attenuation<br><br>R-chart absolute attenuation | Xbar-chart absolute attenuation<br><br>R-chart absolute attenuation |
| *Datasheet* | Table (Datasheet X number of data rows) | Table (Datasheet X number of data rows) |
| *Datapoint* | Default 25 measurements of Tube X on Coating line Y | Default 25 measurements of Tube X on Coating line Y (Possibility to change number of measurement) |
| *Out-of-Control* | Notification of Out-of-Control situation at Tube X and Coating line Y. Attenuation lies outside the control limits | Notification of Out-of-Control situation at Tube X and Coating line Y. Attenuation lies outside the control limits |
| *Xbar-R-Charts At. increase* | *Not available*<br><br>*Not available* | Xbar-chart increase of attenuation with respect to transparent fibre<br><br>R-chart absolute increase attenuation with respect to transparent fibre |

| | | |
|---|---|---|
| *Xbar-R-Charts At. increase* | *Not available*<br><br>*Not available* | Xbar-chart increase of attenuation with respect to coloured fibre<br><br>R-chart absolute increase attenuation with respect to coloured fibre |
| *Control limits* | Show control limits in graphs from CableBuilder | Show control limits in graphs from CableBuilder |
| *Coating line / Tube selection* | *Not available* | Possibility to select desired Coating line and tube |
| *Highlight Out-of-Control* | *Not available* | Detect Out-of-Control situation easily by highlighting the data point |
| *Highlight last measurement* | *Not available* | Find the last measurement of the Coating line by highlighting it |
| *Legenda* | -Dataline<br>-Measurements<br>-Out-of-Control<br>-Average<br>-UCL and LCL | -Dataline<br>-Measurements<br>-Out-of-Control<br>-Average<br>-UCL and LCL |

## 5.5 Controlling process improvements

To sustain the process improvements for the future, we determine several key performance indicators. Using Key performance indicators (KPIs) creates an analytical basis for decision-making and helps to manage the process. Managing with KPIs opens the opportunity to set targets and track progress (Trukhmanov, 2021). A good KPI, should provide the progress towards the desired result, offers a comparison, and track the efficiency of the system (Trukhmanov, 2021). To control the progress and improvements that we have determined in Chapter 5, we define three different KPIs. First, is the control of the measurement errors. To measure the progress, we use the FTR percentage. In Section 4.1.3 we calculated the current number of failures. After the company has implemented the improvements defined in this chapter, the company is able to track the progress and knows whether the process has improved. If the company does not see any improvements, the company could consider implementing stricter prerequisites.

Next to the FTR for the measurement errors, we select KPIs for the fibre optics cables. These KPIs are used for the control charts to see whether the process is in or out of control. Furthermore, the control enables to manage the attenuation of the fibres in real-time. Furthermore, as mentioned in Section 5.4, it is possible to track the progress of the fibres since we can see the measurement values of the last 25 measured reels. This way, we monitor whether the process is performing within the control limits and are able to intervene when necessary. Finally, we can use the capability indices, $C_p$, $C_{pk}$, $P_p$and $P_{pk}$. These indices tell how the process is performing and shows the mean and the process variation. Within a few months after the implementation of SPC on the Coating line, the company can conduct another capability study. Then, the company is able to compare these to the studies of this research and determine the systematic process changes, if any.

Table 23 summarizes the selected KPIs. Furthermore, there is an indication of the current average values of the process as calculated during this research, and the values for which the company should aim. The last column of the table lists the goal values of SPC. These are lower than the current capability values. However, TKF strives for a Six Sigma process. Therefore, the capability values must be larger than the indicated values in Table 23. Besides, due to the inaccuracies regarding the measurement, the actual performance of the coating process is partly hidden. For that reason, we also implement a margin for the capability values because it is not realistic to score as high as the capability values from the table.

*Table 23: Future goals measurement system and capability indices*

| | KPI | Current value (Avg.) | Goal value |
|---|---|---|---|
| *Measurement system* | FTR | 84.06% | 98.00% |
| | | | |
| *SPC* | Cp | +/- 9.00 | >2.0 |
| | Cpk | +/- 9.00 | >2.0 |
| | Pp | +/- 8.00 | >1.5 |
| | Ppk | +/- 8.00 | >1.5 |

To sustain the process improvements after the project closure, we set up a plan of action. First, the measurement system. For this part, it is important to train the operators to work with the MiniMAS and instruct them about how to take care of the workspace. For instance, how to keep the workspace clean and ensure the steps that have been defined in Section 5.1. These guidelines should be mentioned clearly in the training program. Next to this, the operators have to be educated on the SPC software and instruct them what they should do in times of an Out-of-Control situation. Therefore, the operators should follow the plan for what to do in case of an Out-of-Control situation. This plan is available for every operator in their personal account. Finally, to guarantee the quality of the SPC software for the Coating line, we have to conduct a quality check where we compare the software with the package of requirements as defined in Table 22.

## 5.6 Conclusion

To improve the measurement of the attenuation value, we provide several improvements regarding the Measurement, Machine, Man, Environment, Method, and Material. First of all, the workspace should be reorganized to keep it clean and structured. Furthermore, TKF should implement the measurement procedure in the training program since there are many incorrect measurements. Furthermore, we showed that the potential performance of the coating process is twice as high as the current performance, which is partly caused by the incorrect measurement. For this reason, it is also important to educate the operators regarding the MiniMAS measurement. To implement SPC and maintain the process improvements we refer to in Sections 5.3 and 5.5. To measure the process improvements a capability study can be conducted one or two months after the implementation of SPC. Furthermore, the decrease in measurement errors caused by the operators can be measured by calculating the FTR. By monitoring this value, TKF is able to observe whether a better education of operators contributes to a higher FTR percentage.

# 6. Conclusion

This chapter starts with the conclusion in Section 6.1. Then, Section 6.2 provides a recommendation for the company. Finally, Section 6.3 explains the discussion and limitations of the research.

## 6.1 Conclusion

In this research, we studied the attenuation value of fibre optics at TKF. First, we provided a short introduction of the company, introduced the production process of the fibre optics cable, and explained relevant characteristics of the V28-Fibre, V29-Fibre and V30-Fibre on the 'SeC 6' and 'SeC 9'. Furthermore, we discussed the problem context. The main problem for this thesis is the current analysis of the attenuation value of fibre optics reel between consecutive batches. In the initial situation, it was not possible for the company to detect any pattern between the reels and understand the process variation. Implementation of SPC helps to detect these patterns and control the process to reduce the variation. Furthermore, we provided the research questions of the thesis. The aim of the research questions was to get an insight into the current process performance and provide the potential of the process when SPC is implemented. Next, with the research questions, the purpose was to provide a roadmap of how to implement SPC into the Coating line. In the literature review, we provided the theoretical background about the main topics of this thesis. In that chapter, we discussed the most suitable problem-solving method for the problem of this research. We found that the Lean Six Sigma DMAIC method is the most useful because of its approach. Furthermore, we explained the hypothesis tests and elaborated on why to choose SPC as a statistical analysis method to implement on the Coating line at TKF.

During the research, we focussed on three main elements. We started to check the reliability and validity of the measurement system since we first had to determine whether the data is proper to use for the research. In fact, we observed that we cannot accept the MiniMAS measurement system as a reliable and valid system, following the acceptance standards defined by the AIAG. On the other hand, a previous study has already demonstrated that the manual MAS system is reliable and valid. For this reason, we must be careful with recommendations and conclusions based on the data of the MiniMAS since the data is not reliable and valid. However, we wanted to know the current performance of the process in order to compare it with the potential capability of the process. Therefore, we used this data, including the incorrect measurement. Next to this, we conducted an ANOVA study on the position of the fibre in the measurement system. By conducting a two-sample t-test and a test on equal variances at the positions of the fibre, we assume that there is no significant difference between the positions where the fibres are measured. Subsequently, we calculated the FTR percentage of the different tubes. Here, we found a lot of errors regarding the measurement of the attenuation value of a tube due to human operators. So, apparently, the operators do not have enough knowledge about how to measure and which equipment to use to make the measurement procedure easier. These issues regarding the measurement have a large influence on the data since it reduces the reliability of the datasets.

We conducted a two-sample t-test and a test on equal variances to determine the difference between types of fibres and Coating lines. By testing these variables on the difference in mean and variances, we decide whether there is a significant difference between these variables. When we observe that there is a significant difference we cannot use the same control limits. However, by calculating the p-value, we found that it is possible to use the same control limits for the different Coating lines but not for different types of fibres. So, for every fibre, we have to calculate separately the control limits.

After we knew the current process performance, we calculated the potential of the coating process in order to determine the potential of the system. For this study, we used the data from the manual MAS and excluded all the incorrect measurements caused by the MiniMAS and the operators. It was not astonishing that the potential capability is higher than the current process performance. For instance, the V29-Fibre scores were twice as high when we excluded all the measurement errors. Moreover, we calculated the control limits for the Xbar- and R-charts and I- and MR-charts and discussed the benefits of the two types of charts. We decide to use the Xbar- and R-chars since these charts provide information at fibre level which helps to detect sooner the root causes of the patterns and process variation in the system. Furthermore, we discussed whether the implementation of SPC is necessary and what the dashboard of the software should look like. Therefore, we have set up a package of requirements. These requirements explain the necessary functions for SPC in the measurement systems. This package of requirements for the software can be found in Section 5.4. There, we provide an overview of the dashboard and requirements for the two user interfaces. Finally, to sustain the process improvements, we selected several KPIs. With these KPIs, TKF is able to measure and monitor the improvements in the production process of the fibre optics cable after the project closure.

## 6.2 Recommendation

The Twentsche Kabelfabriek is always striving for the highest possible product quality. Last year, TKF started implementing Statistical Process Control on the production process of the fibre optics cable. Currently, SPC is already running on the Colour line production. Now the purpose is to implement this procedure on the Coating line. However, as discussed in this report, there are several challenges that have to be considered before TKF is able to implement SPC on the Coating line.

First of all, the measurement system, especially the MiniMAS has some major errors. In order to improve this system, we advise training all employees that are working with the MiniMAS on how to use this device and what to do in case of a failure. Furthermore, the measurement devices need maintenance on a regular base. Our plan for the maintenance is to check on position, repeatability, and accuracy every quarter. Furthermore, every item and tool that is necessary for the measurement must get a permanent location and the operators should clean the workspace at the end of their shift. Next to this, we recommend conducting another MSA on the MiniMAS with well-trained operators or managers after the maintenance of the measurement system. Since we also observed failures in the measurement system itself, we cannot 100% guarantee the reliability and validity of the MSA conducted in Section 4.1.1. However, the MiniMAS saves a lot of time when measuring multiple fibres at a time. For these reasons, we strongly advise doing another MSA with 10 reels, three operators, and two replication. This way, the actual quality of the measurement system can be determined.

For the implementation of SPC on the Coating line, TKF has to consider several elements. First, we must decide the type of control chart. The advantage of the I- and MR-charts is that these charts use the average attenuation value of a tube. Using these charts, it is less likely to come across an extreme value caused by the measurement system or process. However, since we see that there is a lot of potential in the system, we have decided to use the Xbar- and R-chart. The benefit of the Xbar- and R-charts is that these charts provide information at fibre level which is not possible for the I- and MR-chart. Next to this, in the short-term, it is possible to lower the lower control limit for the MiniMAS to

0.002 as calculated in Section 5.3. This way, we reduce the probability of observing an Out-of-Control situation. By checking the control limits for several weeks, we verify whether the control limits are proper for the process. For the manual MAS and MiniMAS, we advise to take the control limits from Section 5.3, since this measurement system is conforming to the acceptance standards defined by the AIAG and adopted by TKF. Furthermore, the software has to be adapted to make it applicable for the Coating lines at TKF. As mentioned in Section 5.4, the software has to be changed at six different points.

## 6.3 Discussion and Limitations

During the research, we came across some discussion points and limitations. The most significant limitation of the study was the available data. Since we only had data available from 2022, we were limited to the production scheme of 2022. Therefore, we could only use the different types of fibres and tubes which were produced on the Coating lines ‘SeC 6’ and ‘SeC 9’. So, we investigated only four of these combinations. However, we can make approximately 50 combinations of tubes. For follow-up research, we recommend collecting more data on the other combinations and conducting a capability study to determine the control limits of these tubes. Furthermore, TKF desires a control chart for the increase in attenuation with respect to the previous production process step. However, this data is not available yet since the ERP system of TKF is undergoing an overhaul at the moment. So, we were not able to determine the control limits for these control charts.

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# Appendices

## A.1 Dataset

This appendix shows an example of the dataset we used for this research.

| Reel l | Lotnr. | Coating line | Nr. of f | Metingnr. | Kabelnum | CIQ Nummer | Identifier (vezelnr.) | Datum | Tijd | Meetst | lijn nr. | Item nr. | Omschrijving | Omschrijving2 | | Demping verkabelde vezel l | | | MAS/H dmeting |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 446631 | 4466310064 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4466310064 | 1-GREY-12-PINK | 7-01-22 | 16:34:53 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 GREY+1R | | 0.184 | - | - | Handmeting |
| 449280 | 4492800029 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4492800029 | 1-RED-7-ORANGE | 25-01-22 | 10:13:07 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 RED | | 0.184 | - | - | Handmeting |
| 449280 | 4492800028 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4492800028 | 1-RED-11-TURQUOISE | 25-01-22 | 10:37:45 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 RED | | 0.184 | - | - | Handmeting |
| 447691 | 4476910100 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4476910100 | 1-GREEN-2-BLUE | 26-01-22 | 10:10:44 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 GREEN+2R | | 0.184 | - | - | Handmeting |
| 447691 | 4476910052 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4476910052 | 1-TURQUOISE-1-RED | 26-01-22 | 21:15:57 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 TURQUOISE+1R | | 0.184 | - | - | Handmeting |
| 447691 | 4476910143 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4476910143 | 1-LIGHTGREEN-2-BLUE | 27-01-22 | 11:13:31 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 LIGHTGREEN+2R | | 0.184 | - | - | Handmeting |
| 447691 | 4476910016 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4476910016 | 1-WHITE-2-BLUE | 27-01-22 | 15:07:17 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 WHITE+1R | | 0.184 | - | - | Handmeting |
| 447691 | 4476910106 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4476910106 | 1-VIOLET-2-BLUE | 27-01-22 | 19:13:38 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 VIOLET+2R | | 0.184 | - | - | Handmeting |
| 447369 | 4473690142 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4473690142 | 1-LIGHTGREEN-8-GREY | 1-02-22 | 00:22:06 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 LIGHTGREEN+2R | | 0.184 | - | - | Handmeting |
| 447369 | 4473690142 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4473690142 | 1-LIGHTGREEN-10-BLACK | 1-02-22 | 00:22:38 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 LIGHTGREEN+2R | | 0.184 | - | - | Handmeting |
| 447369 | 4473690166 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4473690166 | 1-LIGHTGREEN-9-BROWN | 1-02-22 | 14:58:19 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 LIGHTGREEN+1R | | 0.184 | - | - | Handmeting |
| 447369 | 4473690170 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4473690170 | 1-GREEN-3-GREEN | 1-02-22 | 22:44:01 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 GREEN+1R | | 0.184 | - | - | Handmeting |
| 448567 | 4485670118 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4485670118 | 1-ORANGE-3-GREEN | 2-02-22 | 14:50:53 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 ORANGE+2R | | 0.184 | - | - | Handmeting |
| 448567 | 4485670118 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4485670118 | 1-ORANGE-9-BROWN | 2-02-22 | 14:52:27 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 ORANGE+2R | | 0.184 | - | - | Handmeting |
| 448567 | 4485670118 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4485670118 | 1-ORANGE-11-TURQUOISE | 2-02-22 | 14:52:52 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 ORANGE+2R | | 0.184 | - | - | Handmeting |
| 450006 | 4500060023 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4500060023 | 1-BLUE-6-WHITE | 3-02-22 | 13:14:35 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 BLUE | | 0.184 | - | - | Handmeting |
| 448567 | 4485670052 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4485670052 | 1-TURQUOISE-7-ORANGE | 4-02-22 | 03:51:16 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 TURQUOISE+1R | | 0.184 | - | - | Handmeting |
| 448695 | 4486950107 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4486950107 | 1-VIOLET-1-RED | 8-02-22 | 08:01:33 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 VIOLET+2R | | 0.184 | - | - | Handmeting |
| 448695 | 4486950064 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4486950064 | 1-GREY-4-YELLOW | 8-02-22 | 13:17:45 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 GREY+1R | | 0.184 | - | - | Handmeting |
| 448695 | 4486950138 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4486950138 | 1-GREY-11-TURQUOISE | 8-02-22 | 17:43:43 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 GREY+2R | | 0.184 | - | - | Handmeting |
| 448695 | 4486950168 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4486950168 | 1-GREEN-2-BLUE | 8-02-22 | 23:19:33 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 GREEN+1R | | 0.184 | - | - | Handmeting |
| 448695 | 4486950168 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4486950168 | 1-GREEN-3-GREEN | 8-02-22 | 23:19:42 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 GREEN+1R | | 0.184 | - | - | Handmeting |
| 448695 | 4486950168 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4486950168 | 1-GREEN-4-YELLOW | 8-02-22 | 23:19:50 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 GREEN+1R | | 0.184 | - | - | Handmeting |
| 448695 | 4486950168 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4486950168 | 1-GREEN-6-WHITE | 8-02-22 | 23:20:06 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 GREEN+1R | | 0.184 | - | - | Handmeting |
| 448567 | 4485670158 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4485670158 | 1-ORANGE-1-RED | 9-02-22 | 10:04:42 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 ORANGE+2R | | 0.184 | - | - | Handmeting |
| 448695 | 4486950191 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4486950191 | 1-ORANGE-10-BLACK | 10-02-22 | 12:34:15 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 ORANGE+1R | | 0.184 | - | - | Handmeting |
| 448695 | 4486950016 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4486950016 | 1-WHITE-10-BLACK | 10-02-22 | 23:51:25 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 WHITE+1R | | 0.184 | - | - | Handmeting |
| 448696 | 4486960054 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4486960054 | 1-TURQUOISE-2-BLUE | 16-02-22 | 04:07:20 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 TURQUOISE+1R | | 0.184 | - | - | Handmeting |
| 448696 | 4486960168 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4486960168 | 1-RED-10-BLACK | 16-02-22 | 08:09:20 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 RED+1R | | 0.184 | - | - | Handmeting |
| 449495 | 4494950090 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4494950090 | 1-GREEN-6-WHITE | 23-02-22 | 16:19:51 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 GREEN | | 0.184 | - | - | Handmeting |
| 449495 | 4494950092 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4494950092 | 1-GREEN-6-WHITE | 23-02-22 | 16:45:53 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 GREEN | | 0.184 | - | - | Handmeting |
| 449495 | 4494950096 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4494950096 | 1-GREEN-6-WHITE | 23-02-22 | 17:46:30 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 GREEN | | 0.184 | - | - | Handmeting |
| 449495 | 4494950096 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4494950096 | 1-GREEN-8-GREY | 23-02-22 | 17:47:14 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 GREEN | | 0.184 | - | - | Handmeting |
| 449495 | 4494950058 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4494950058 | 1-BLUE-3-GREEN | 23-02-22 | 21:17:40 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 BLUE | | 0.184 | - | - | Handmeting |
| 449495 | 4494950058 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4494950058 | 1-BLUE-5-VIOLET | 23-02-22 | 21:19:28 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 BLUE | | 0.184 | - | - | Handmeting |
| 449495 | 4494950058 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4494950058 | 1-BLUE-6-WHITE | 23-02-22 | 21:19:45 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 BLUE | | 0.184 | - | - | Handmeting |
| 449495 | 4494950024 | GV SEC COATINGLIJN 6 | 12 | 2 | 450 | 4494950024 | 1-YELLOW-7-ORANGE | 24-02-22 | 08:49:19 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 YELLOW | | 0.184 | - | - | Handmeting |
| 449495 | 4494950048 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4494950048 | 1-RED-8-GREY | 24-02-22 | 07:43:41 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 RED | | 0.184 | - | - | Handmeting |
| 449495 | 4494950022 | GV SEC COATINGLIJN 6 | 12 | 1 | 450 | 4494950022 | 1-YELLOW-8-GREY | 24-02-22 | 08:18:48 | mas3tel2 | Onbekend | 7.5E+08 | ST002 Ø1.30/1.0C | 12xSM G.657.A2 V29 YELLOW | | 0.184 | - | - | Handmeting |

*Figure 28: Example of the data*

## A.2 Statistical characteristics

In this Appendix, we provide the summary report of the fibres on different Coating lines. These summaries contain the mean, standard deviation, skewness, kurtosis, and sample size.

### A.2.1 SeC 6

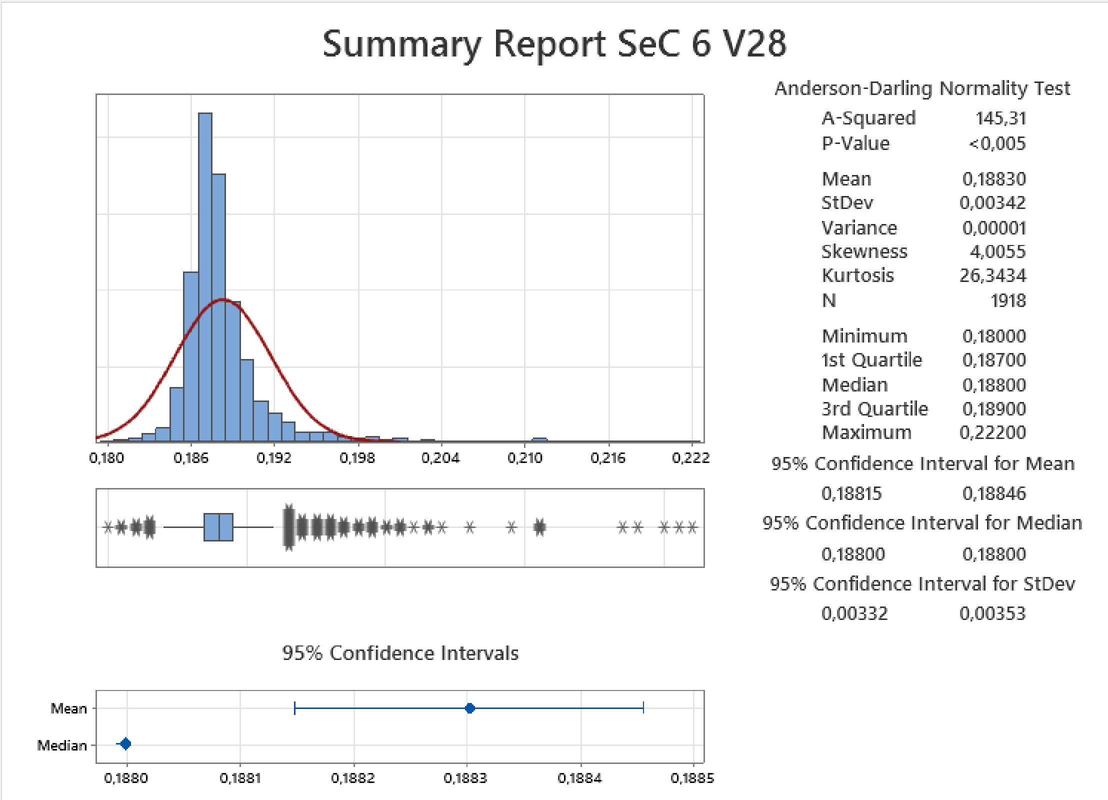


*Figure 29: Histogram SeC 6 V28 weeks 1-20 2022 1550 nm / ST002 Ø1.30/1.00 /  160 Tubes*

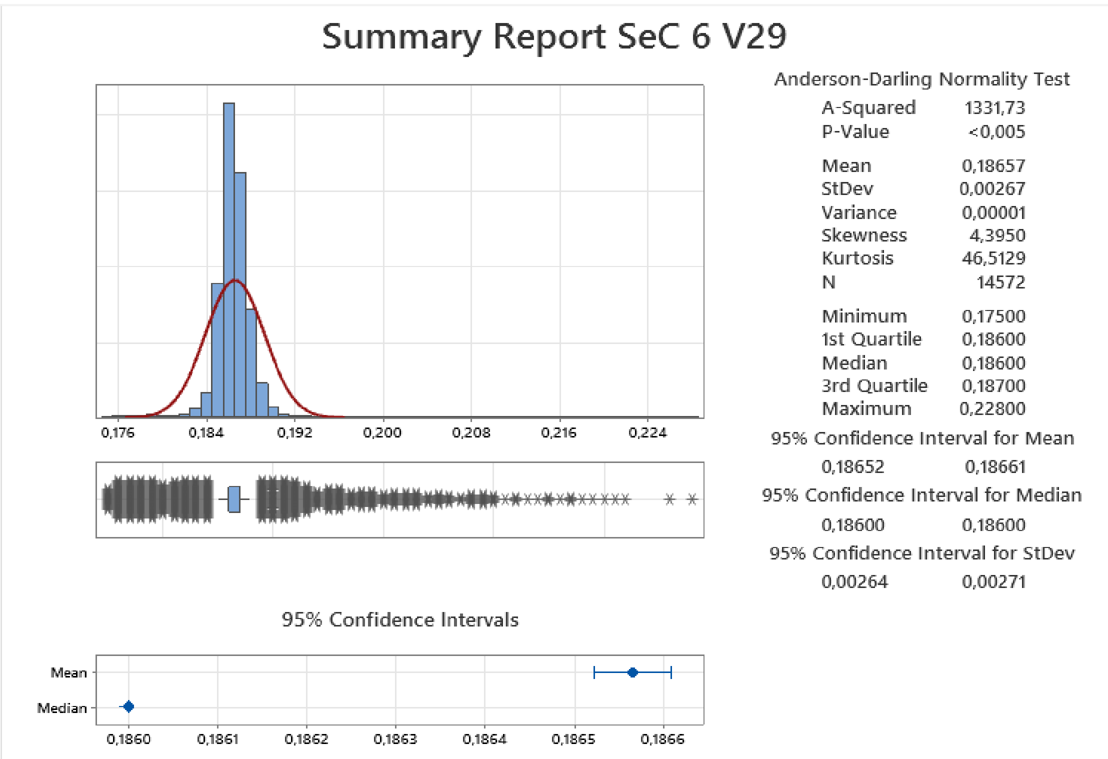


*Figure 30 SeC 6 V29 weeks 1-20 2022 1550 nm / ST002 Ø1.30/1.00 / 1214 Tubes*

### A.2.2 SeC 9

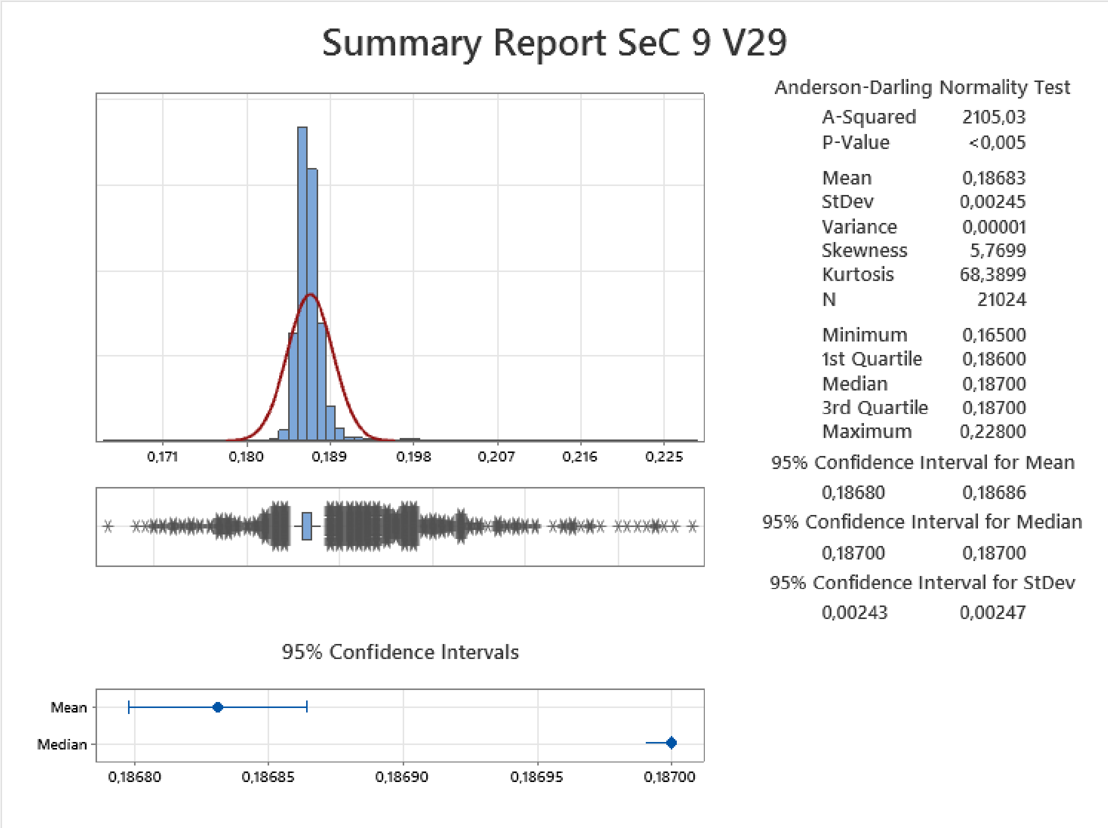


*Figure 31: Histogram SeC 9 V29 weeks 1-20 2022 1550 nm / ST002 Ø1.30/1.00 / 1752 Tubes*

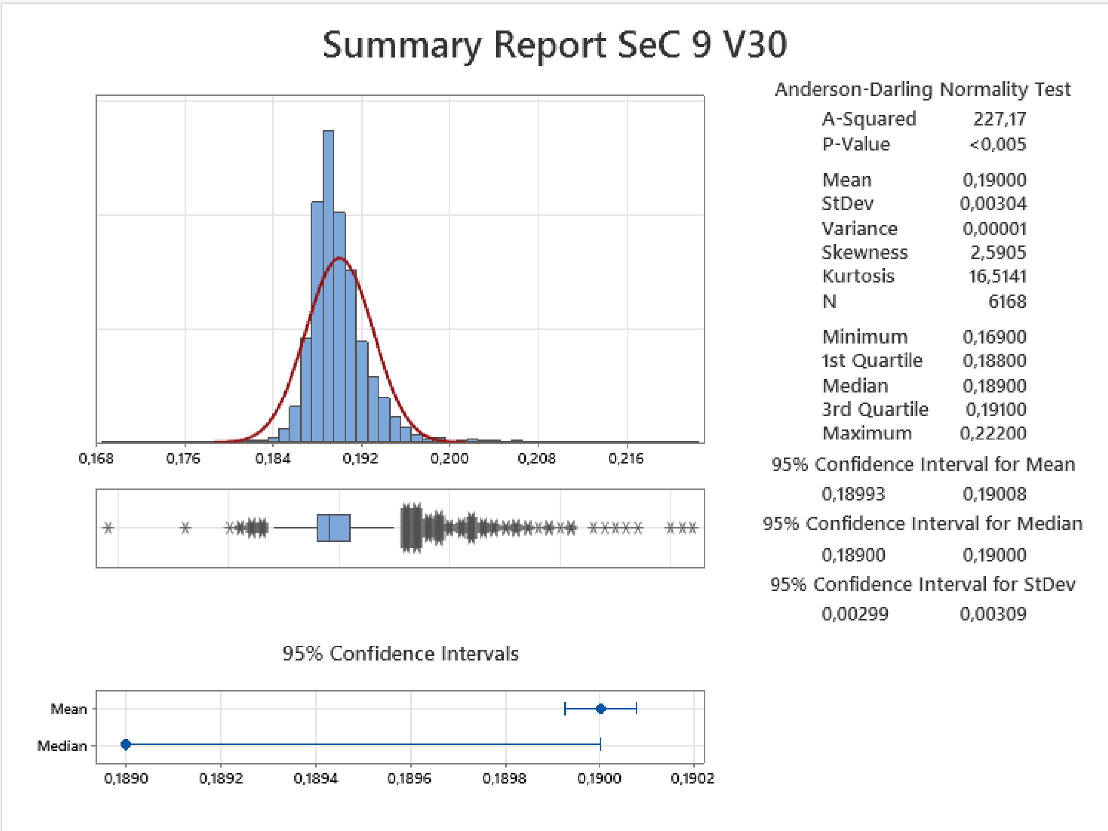


*Figure 32: SeC 9 V30 weeks 1-20 2022 1550 nm / ST004 Ø1.15/0.90 / 514 Tubes*

## A.3 Distribution identification

Tables 24 and 25 provides the information of the individual Distribution Identification for the fourteen different distributions on the 'SeC 6' and 'SeC 9'.

### A.3.1 SeC 6

*Table 24: SeC 6  Individual Distribution Identification*

| **Distribution** | **ST002 / SeC 6 V28** | | | **ST002 / SeC 6 V29** | | |
|---|---|---|---|---|---|---|
| | *AD* | *P* | *LRT P* | *AD* | *P* | *LRT P* |
| *Normal* | 1331,734 | <0,005 | | 22,418 | <0,005 | |
| *Box-Cox Transformation* | 1077,061 | <0,005 | | 12,616 | <0,005 | |
| *Lognormal* | 1272,282 | <0,005 | | 20,421 | <0,005 | |
| *3-Parameter Lognormal* | 1107,743 | * | 0,000 | 2,328 | * | 0,000 |
| *Exponential* | 6560,297 | <0,003 | | 230,567 | <0,003 | |
| *2-Parameter Exponential* | 4928,565 | <0,010 | 0,000 | 36,701 | <0,010 | 0,000 |
| *Weibull* | 3296,230 | <0,010 | | 53,025 | <0,010 | |
| *3-Parameter Weibull* | 2137,971 | <0,005 | 0,000 | 7,322 | <0,005 | 0,000 |
| *Smallest Extreme Value* | 3437,174 | <0,010 | | 57,306 | <0,010 | |
| *Largest Extreme Value* | 1760,705 | <0,010 | | 5,245 | <0,010 | |
| *Gamma* | 1291,814 | <0,005 | | 21,053 | <0,005 | |
| *3-Parameter Gamma* | 1146,497 | * | 0,000 | 4,102 | * | 0,000 |
| *Logistic* | 492,417 | <0,005 | | 12,679 | <0,005 | |
| *Loglogistic* | 486,216 | <0,005 | | 11,864 | <0,005 | |
| *3-Parameter Loglogistic* | 470,604 | * | 0,000 | 2,190 | * | 0,000 |

### A.3.2 SeC 9

*Table 25: SeC 9  Individual Distribution Identification*

| **Distribution** | **ST002 / SeC 9 V29** | | | **ST004 / SeC 9 V30** | | |
|---|---|---|---|---|---|---|
| | *AD* | *P* | *LRT P* | *AD* | *P* | *LRT P* |
| *Normal* | 2105,029 | <0,005 | | 227,169 | <0,005 | |
| *Box-Cox Transformation* | 1621,491 | <0,005 | | 154,738 | <0,005 | |
| *Lognormal* | 1996,846 | <0,005 | | 212,007 | <0,005 | |
| *3-Parameter Lognormal* | 1683,667 | * | 0,000 | 154,019 | * | 0,000 |
| *Exponential* | 9488,006 | <0,003 | | 2755,819 | <0,003 | |
| *2-Parameter Exponential* | 8419,778 | <0,010 | 0,000 | 2219,599 | <0,010 | 0,000 |
| *Weibull* | 5148,744 | <0,010 | | 854,480 | <0,010 | |
| *3-Parameter Weibull* | 5022,923 | <0,005 | 0,000 | 551,287 | <0,005 | 0,000 |
| *Smallest Extreme Value* | 5345,525 | <0,010 | | 913,082 | <0,010 | |
| *Largest Extreme Value* | 3341,804 | <0,010 | | 348,688 | <0,010 | |
| *Gamma* | 2031,844 | <0,005 | | 216,808 | <0,005 | |
| *3-Parameter Gamma* | 264219,640 | * | 1,000 | 32790,301 | * | 1,000 |
| *Logistic* | 803,476 | <0,005 | | 106,540 | <0,005 | |
| *Loglogistic* | 791,860 | <0,005 | | 102,908 | <0,005 | |
| *3-Parameter Loglogistic* | 743,265 | * | 0,000 | 82,234 | * | 0,000 |

## A.4 Control charts manual MAS & MiniMAS

For the control charts in this appendix, we use the data from the manual MAS and MiniMAS. Besides, the data from the measurement errors is included. In Appendix A.4.1 and A.4.2, we exhibit both types of control charts we used during this research, the Xbar- and R-charts and the I- and MR-charts.

### A.4.1 SeC 6 control charts

At Figure 33, we observe some drifts for the first 20 weeks of 2022, for instance, at sample 120. On the other hand, we see in sample 50 an increase in common variation. However overall, the 'SeC 6' is performing stable and predictable.

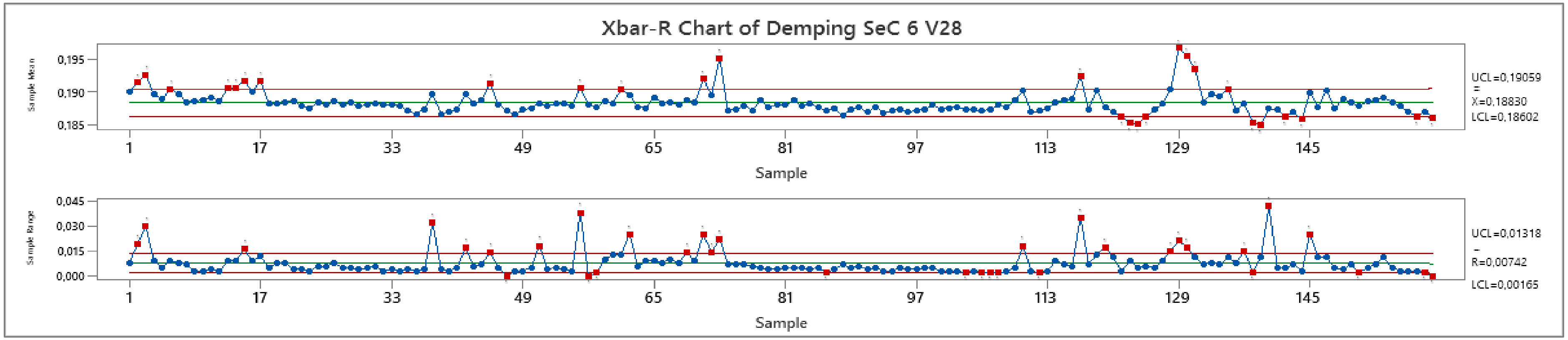


*Figure 33: Xbar-R chart SeC 6 V28 weeks 1-20 2022 1550 nm / ST002 Ø1.30/1.00 / 160 Tubes / manual MAS – MiniMAS*

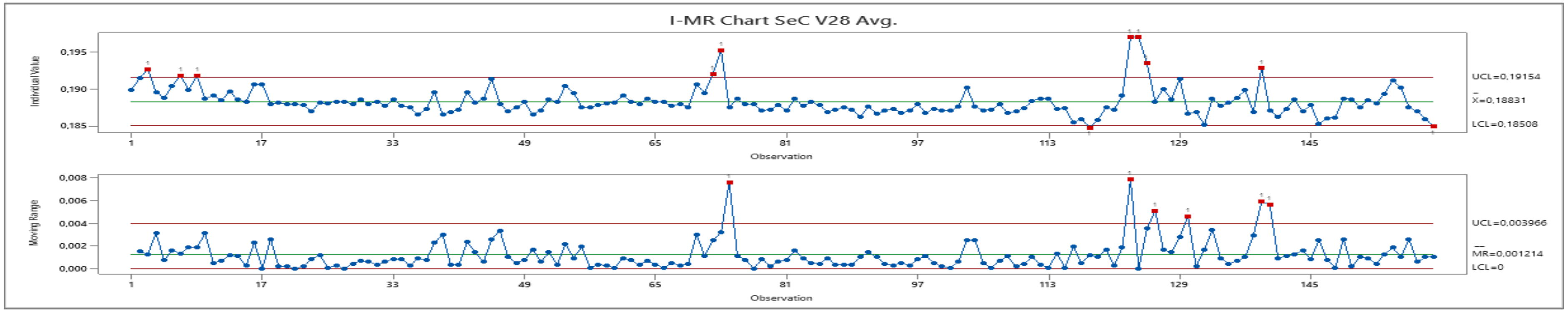


*Figure 34: I-MR chart SeC 6 V28 weeks 1-20 2022 1550 nm / ST002 Ø1.30/1.00 / 160 Tubes / manual MAS – MiniMAS*

At the samples 1100 to 1200 in the graph from Figure 35, we observe a drift. We know that in week 18 TKF introduced a new Jelly for the production of the tubes. After investigating the drift, we discovered that this drift is caused by improper measurement through the operators.

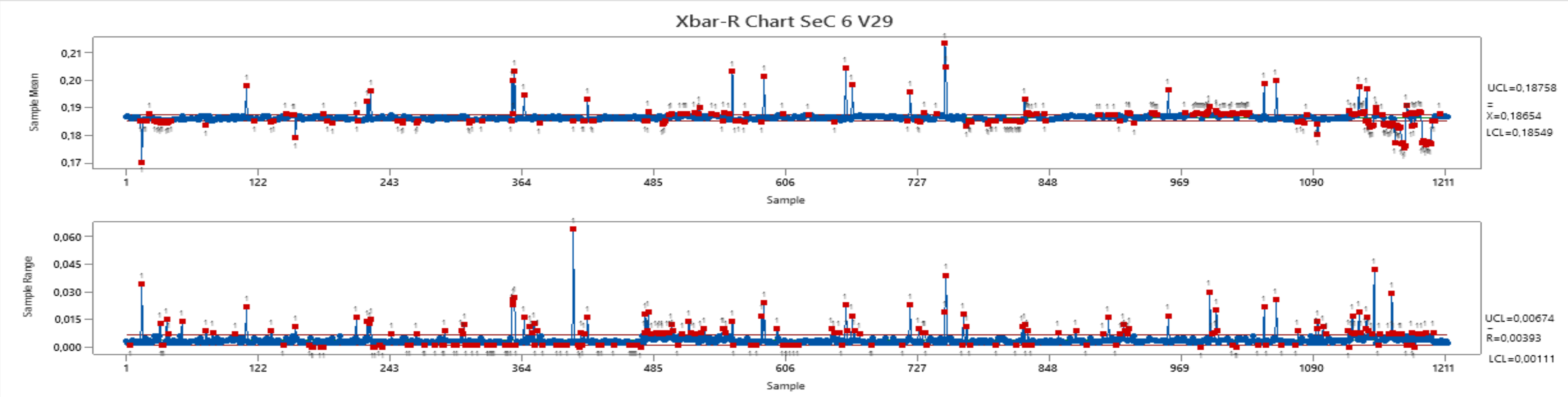


*Figure 35: Xbar-R chart SeC 6 V29 weeks 1-20 2022 1550 nm / ST002 Ø1.30/1.00 / 1213 Tubes / manual MAS – MiniMAS*

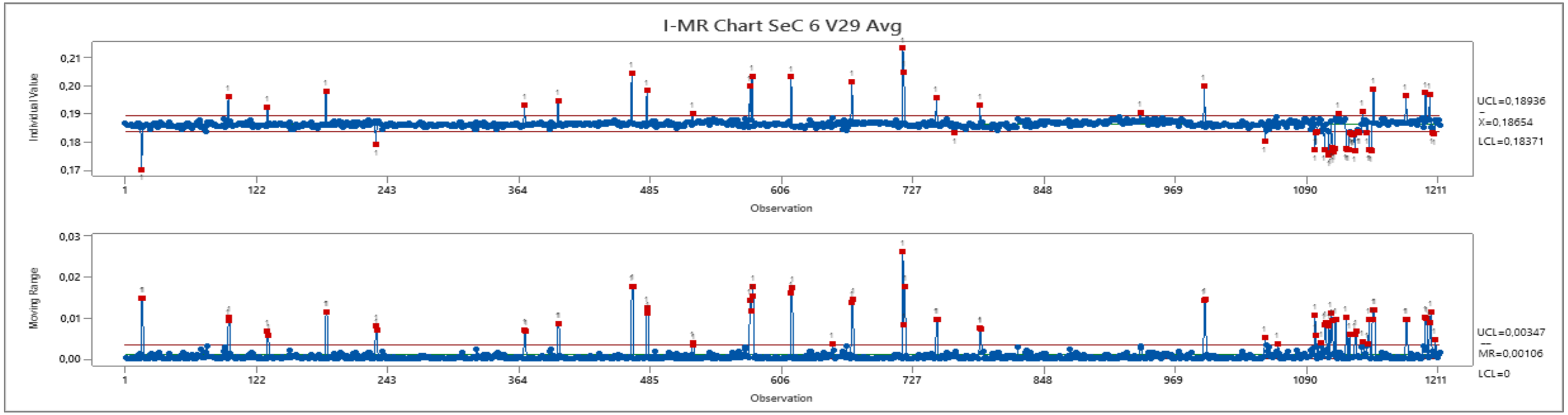


*Figure 36: I-MR chart SeC 6 V29 weeks 1-20 2022 1550 nm / ST002 Ø1.30/1.00 / 1213 Tubes / manual MAS - MiniMAS*

### A.4.2 SeC 9 control charts

At Figure 37, the overall stability of the process is quite good. In fact, only for the samples 1450 to 1600 there are two drifts in the graphs. After investigation, we know that this drift is also caused by improper measurement from the operators.

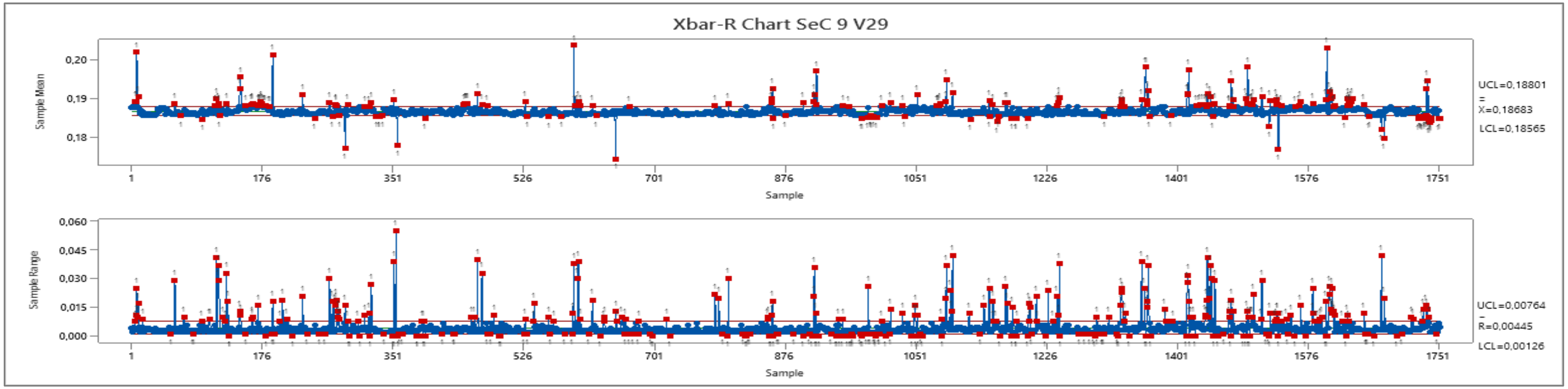


*Figure 37: Xbar-R chart SeC 9 V29 weeks 1-20 2022 1550 nm / ST002 Ø1.30/1.00 / 1751 Tubes / manual MAS – MiniMAS*

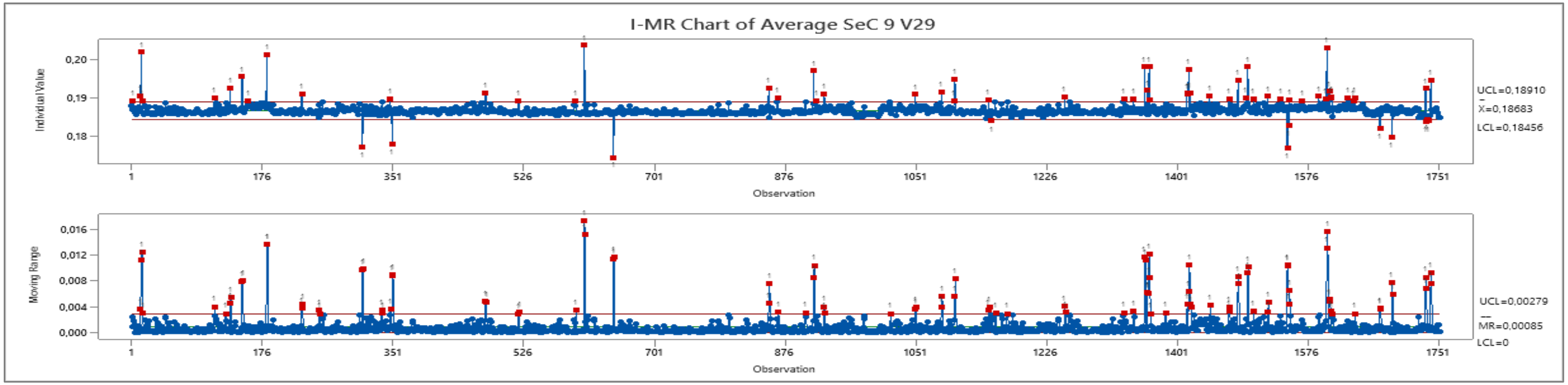


*Figure 38: I-MR chart SeC 9 V29 weeks 1-20 2022 1550 nm / ST002 Ø1.30/1.00 / 1751 Tubes / manual MAS – MiniMAS*

When we look at Figure 39, then the graphs show some drifts and a lot of out-of-control situations. The figure clearly indicates a drift at samples 109 and 402. Both of these drifts are due to improper measurement.

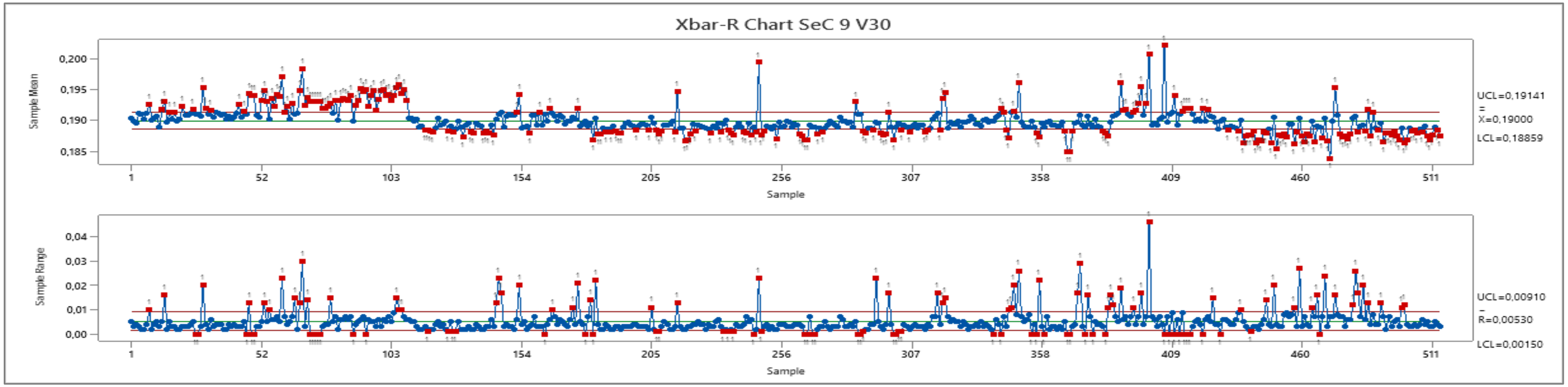


*Figure 39: Xbar-R chart SeC 9 V30 weeks 1-20 2022 1550 nm / ST004 Ø1.15/0.90 / 513 Tubes / manual MAS – MiniMAS*

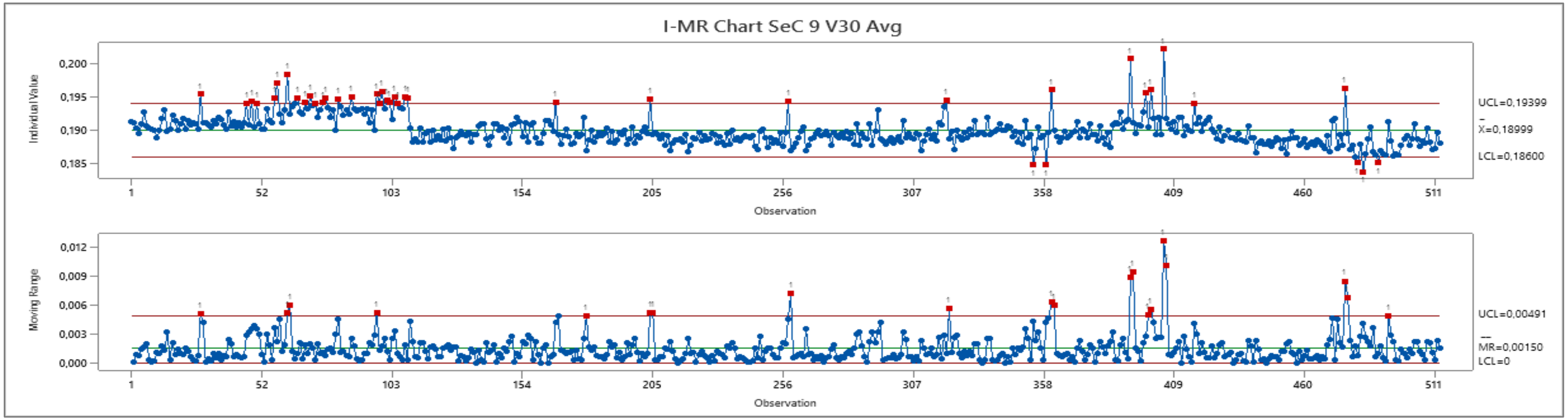


*Figure 40: I-MR chart SeC 9 V30 weeks 1-20 2022 1550 nm / ST004 Ø1.15/0.90 / 513 Tubes / manual MAS – MiniMAS*

## A.5 Control charts manual MAS

For the control charts in this appendix, we use only the correct data from the manual MAS, and we exclude the data from the incorrect measurement. In Appendix A.5.1 and A.5.2, we exhibit both types of control charts we used during this research, the Xbar- and R-charts and the I- and MR-charts.

### A.5.1 SeC 6 control charts

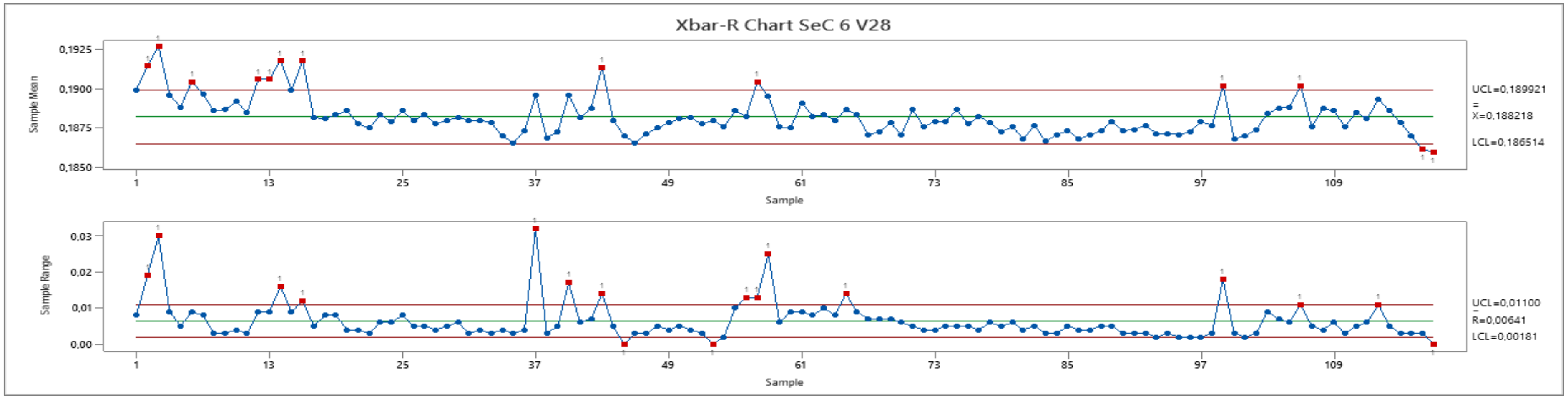


*Figure 41: Xbar-R chart SeC 6 V28 weeks 1-20 2022 1550 nm / ST002 Ø1.30/1.00 / 111 Tubes / manual MAS*

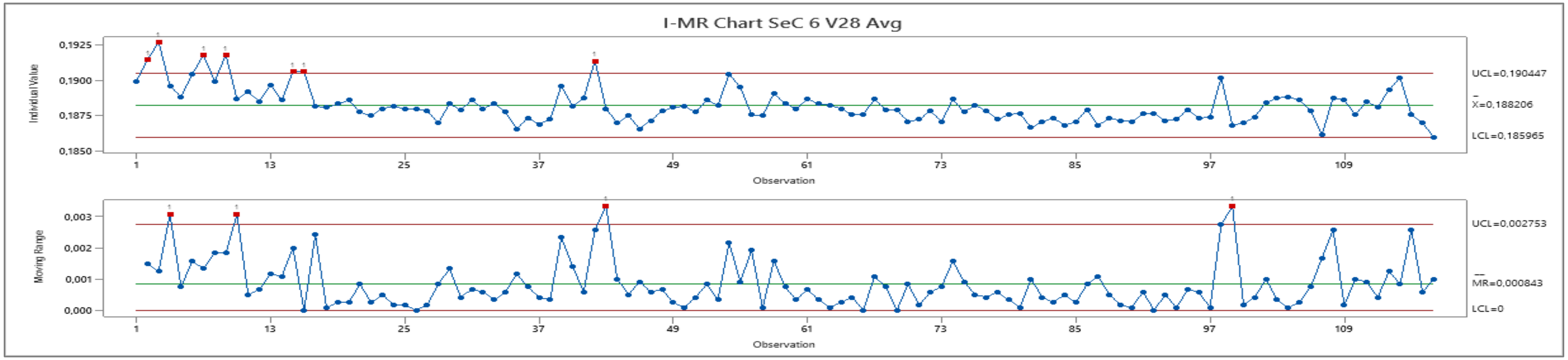


*Figure 42: I-MR chart SeC 6 V28 weeks 1-20 2022 1550 nm / ST002 Ø1.30/1.00 / 111 Tubes / manual MAS*

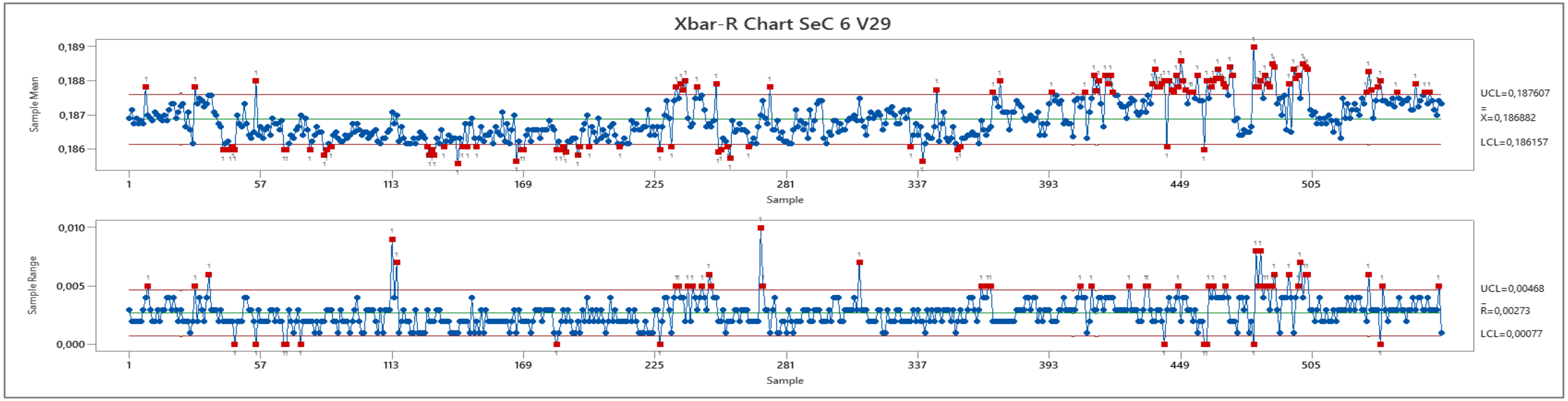


*Figure 43: Xbar-R chart SeC 6 V29 weeks 1-20 2022 1550 nm / ST002 Ø1.30/1.00 / 559 Tubes / manual MAS*

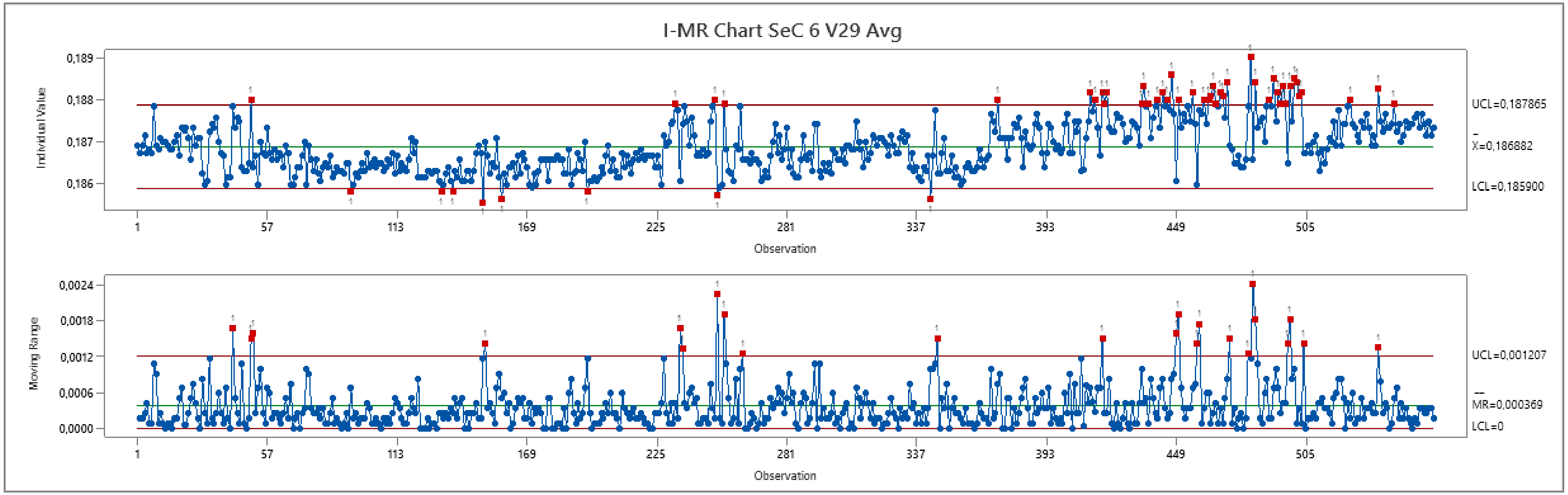


*Figure 44: I-MR chart SeC 6 V29 weeks 1-20 2022 1550 nm / ST002 Ø1.30/1.00 / 559 Tubes / manual MAS*

## A.5.2 SeC 9 control charts

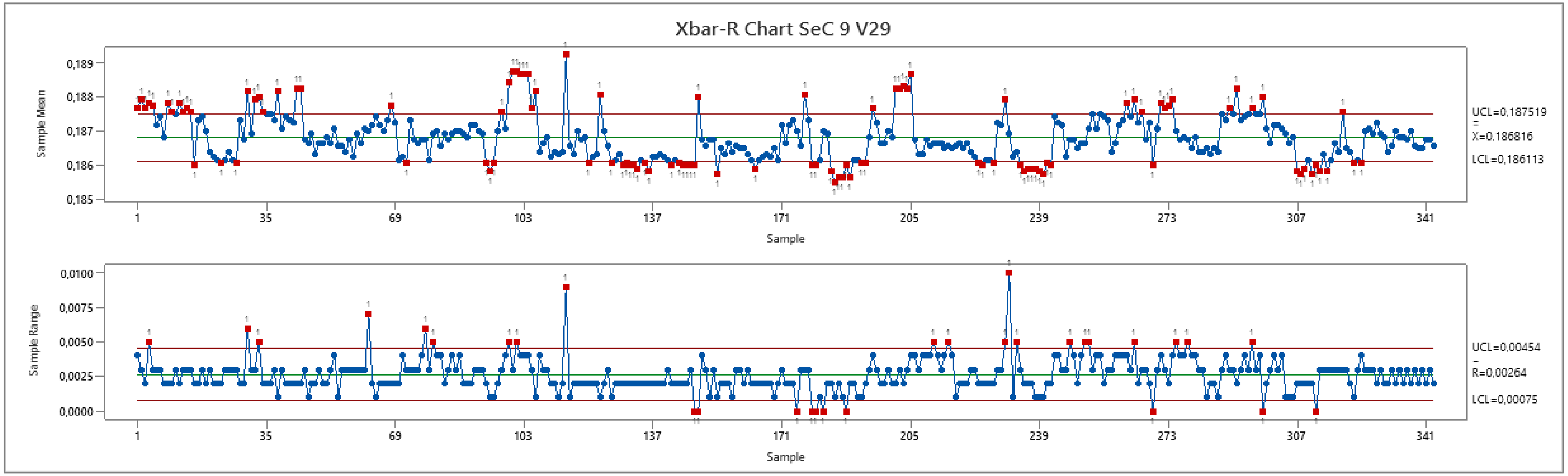


*Figure 45: Xbar-R chart SeC 9 V29 weeks 1-20 2022 1550 nm / ST002 Ø1.30/1.00 / 343 Tubes / manual MAS*

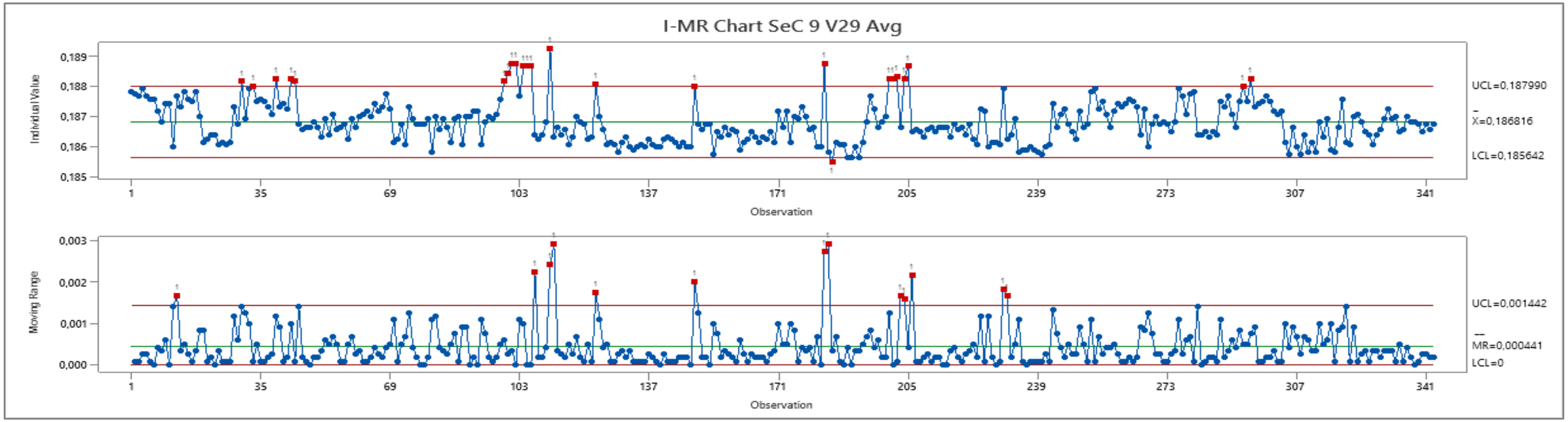


*Figure 46: I-MR chart SeC 9 V29 weeks 1-20 2022 1550 nm / ST002 Ø1.30/1.00 / 343 Tubes / manual MAS*

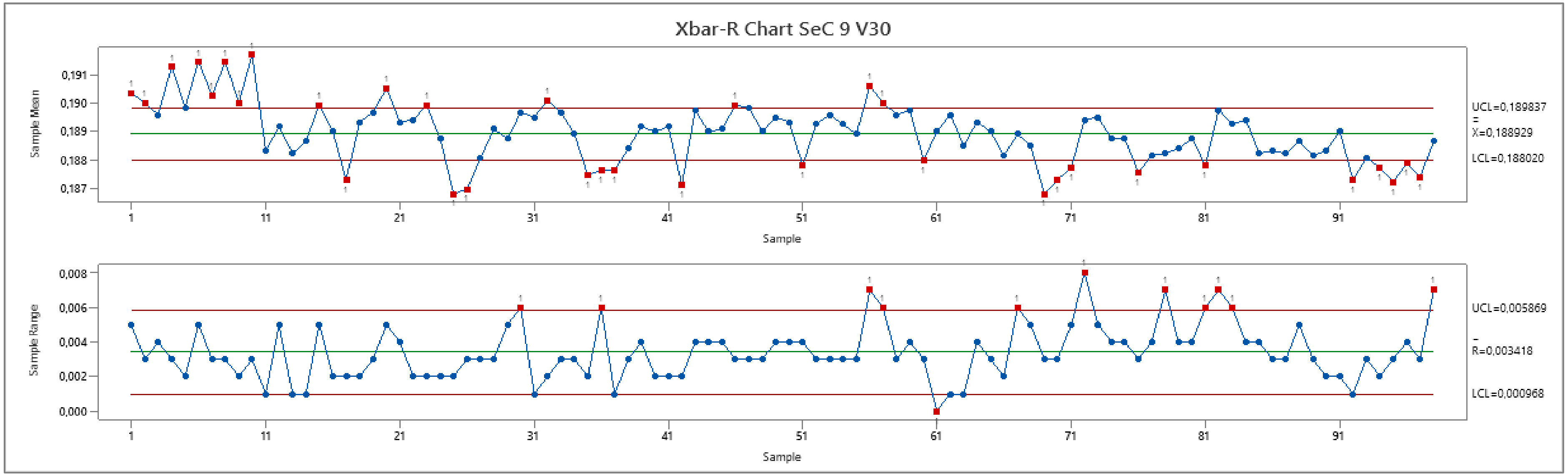


*Figure 47: Xbar-R chart SeC 9 V30 weeks 1-20 2022 1550 nm / ST004 Ø1.15/0.90 / 98 Tubes / manual MAS*

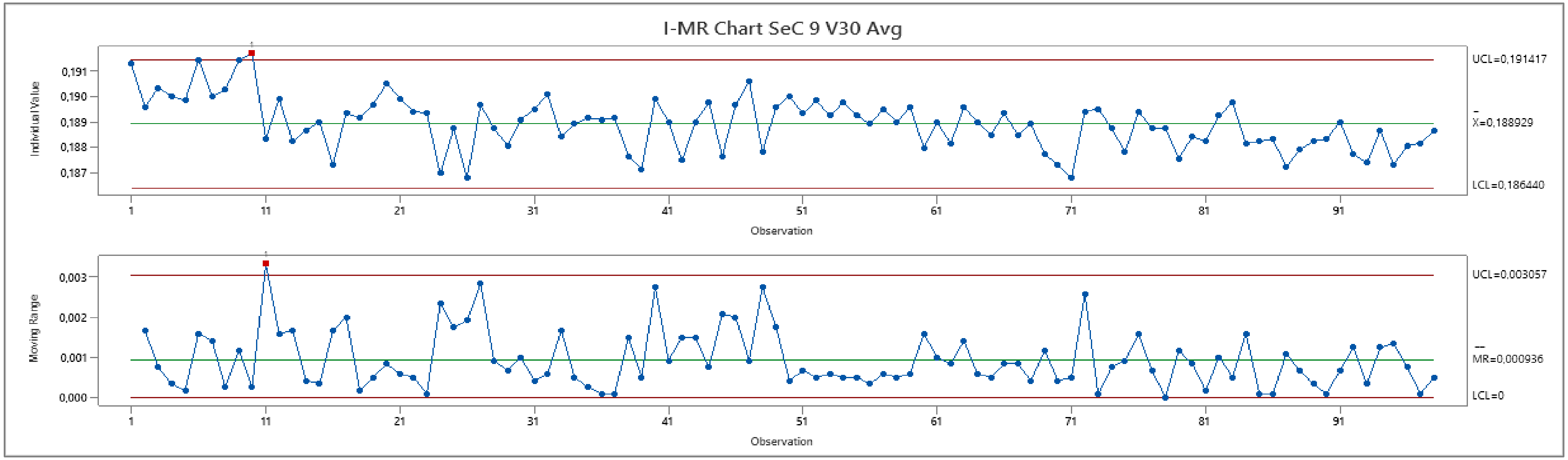


*Figure 48: I-MR chart SeC 9 V30 weeks 1-20 2022 1550 nm / ST004 Ø1.15/0.90 / 98 Tubes / manual MAS*

## A.6 Worked out hypothesis test

In this appendix we worked out the two-sample t-tests and tests on equal variances which we used in this research.

### A.6.1 SeC 6

For the hypothesis tests on the SeC 6, we use the descriptive characteristic in Table 26.

*Table 26: Descriptive statistics SeC 6*

| Sample | N | Mean | St.Dev | SE Mean |
|---|---|---|---|---|
| *SeC 6 V28* | 1,507 | 0.18816 | 0.00245 | 0.000063 |
| *SeC 6 V29* | 7,015 | 0.18687 | 0.00113 | 0.000013 |

First, we conduct the two-sample t-test between the V28-Fibre and the V29-Fibre:

**Method:**
$\mu_1$: population mean of SeC 6 / ST002 Ø1.30/1.00 / V28
$\mu_2$: population mean of SeC 6 / ST002 Ø1.30/1.00 / V29
Difference: $\mu_1 - \mu_2$

| T-Value | DF | P-Value |
|---|---|---|
| 31.43 | 8,520 | 0.000 |

*Null hypothesis:* $H_0: \mu_1 - \mu_2 = 0$
*Alternative hypothesis:* $H_1: \mu_1 - \mu_2 \neq 0$

Second, we conduct the test on equal variance between the V28-Fibre and the V29-Fibre:

**Method:** V28 vs V29
$\sigma_1$: standard deviation of SeC 6 / ST002 Ø1.30/1.00 / V28
$\sigma_2$: standard deviation of SeC 6 / ST002 Ø1.30/1.00 / V29
Ratio: $\sigma_1/\sigma_2$

*Null hypothesis:* $H_0: \sigma_1 / \sigma_2 = 1$
*Alternative hypothesis:* $H_1: \sigma_1 / \sigma_2 \neq 1$

| Method | Test Statistic | DF1 | DF2 | P-Value |
|---|---|---|---|---|
| Bonett | * | | | 0.000 |
| Levene | 374.01 | 1 | 8,520 | 0.000 |

Significance level: $\alpha = 0{,}05$

### A.6.2 SeC 9

For the hypothesis tests on the SeC 9, we use the descriptive characteristic in Table 27.

*Table 27: Descriptive statistics SeC 9*

| Sample | N | Mean | St.Dev | SE Mean |
|---|---|---|---|---|
| *SeC 9 V29* | 4,288 | 0.18687 | 0.00116 | 0.000018 |
| *SeC 9 V30* | 5,890 | 0.18967 | 0.00204 | 0.000027 |

First, we conduct the two-sample t-test between the V29-Fibre and the V30-Fibre:

**Method:**
$\mu_1$: population mean of SeC 6 / ST002 Ø1.30/1.00 / V29
$\mu_2$: population mean of SeC 6 / ST004 Ø1.15/0.90 / V30
Difference: $\mu_1 - \mu_2$

| T-Value | DF | p-value |
|---|---|---|
| 31.43 | 8,520 | 0.000 |

*Null hypothesis:* $H_0: \mu_1 - \mu_2 = 0$
*Alternative hypothesis:* $H_1: \mu_1 - \mu_2 \neq 0$

Second, we conduct the test on equal variance between the V28-Fibre and the V29-Fibre:

**Method:** V29 vs V30
$\sigma_1$: standard deviation of SeC 6 / ST002 Ø1.30/1.00 / V29
$\sigma_2$: standard deviation of SeC 9 / ST004 Ø1.15/0.90 / V30
Ratio: $\sigma_1/\sigma_2$

*Null hypothesis:* $H_0$: $\sigma_1 / \sigma_2 = 1$
*Alternative hypothesis:* $H_1$: $\sigma_1 / \sigma_2 \neq 1$

Significance level: $\alpha = 0{,}05$

| Method | Test Statistic | DF1 | DF2 | p-value |
|---|---|---|---|---|
| Bonett | * | | | 0.000 |
| Levene | 878.18 | 1 | 10,176 | 0.000 |

## A.6.3 SeC 6 & SeC 9

For the hypothesis tests on the SeC 6, we use the descriptive characteristic in Table 28.

*Table 28: Descriptive statistics SeC 6*

| Sample | N | Mean | St.Dev | SE Mean |
|---|---|---|---|---|
| *SeC 6 V29* | 7,015 | 0.18687 | 0.00113 | 0.000014 |
| *SeC 9 V29* | 4,288 | 0.18687 | 0.00116 | 0.000021 |

First, we conduct the two-sample t-test between the V28-Fibre and the V29-Fibre:

**Method:**
$\mu_1$: population mean of SeC 6 / ST002 Ø1.30/1.00 / V29
$\mu_2$: population mean of SeC 9 / ST002 Ø1.30/1.00 / V29
Difference: $\mu_1 - \mu_2$

*Null hypothesis:* $H_0$: $\mu_1 - \mu_2 = 0$
*Alternative hypothesis:* $H_1$: $\mu_1 - \mu_2 \neq 0$

| T-Value | DF | p-value |
|---|---|---|
| 1.88 | 11,301 | 0.061 |

Second, we conduct the test on equal variance between the V28-Fibre and the V29-Fibre:

**Method:** V28 vs V29
$\sigma_1$: standard deviation of SeC 6 / ST002 Ø1.30/1.00 / V28
$\sigma_2$: standard deviation of SeC 6 / ST002 Ø1.30/1.00 / V29
Ratio: $\sigma_1/\sigma_2$

*Null hypothesis:* $H_0$: $\sigma_1 / \sigma_2 = 1$
*Alternative hypothesis:* $H_1$: $\sigma_1 / \sigma_2 \neq 1$

Significance level: $\alpha = 0{,}05$

| Method | Test Statistic | DF1 | DF2 | p-value |
|---|---|---|---|---|
| Bonett | * | 1 | | 0.134 |
| Levene | 6.32 | 1 | 11,301 | 0.012 |