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PROVIDING RECOMMENDATIONS FOR REDUCING MEAN AND VARIABILITY IN ATTENUATION OF OPTICAL FIBRE CABLES AT TKF'S END CONTROL

BACHELOR THESIS

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Preface

Dear reader,

The research has been carried out at the fibre optics cable facility at the premises of TKF's production facility in Haaksbergen. During this research, the main aim was to provide insights into how to improve the attenuation mean and spread for fibre optic cables by introducing statistical process control and providing insights into improvements on the production level.

I would like to thank all employees that helped me during my time at TKF. The employees were always helpful with answering questions about the production process and possible improvements. With special thanks to my company supervisor Alfons ten Tije, for helping me find my way around the company and overall learning me about the process, statistics and Minitab. Additionally helping me out by answering questions and giving me the right guidance.

I would also give special thanks to the university supervisors: Rogier Harmelink and Matthieu van der Heijden. For the guidance and feedback for the intermediate reports and overall guidance in the project. The feedback helped me to correctly structure the research and improve the quality of the report and research.

Enjoy reading my thesis.

Kind Regards,

Raphael Ozo

Enschede, April 2023

Management summary

Problem definition

TKF produces fibre optic cables for the telecommunication industry. These cables must comply with strict quality standards for them to be useful to the customers. Here the main quality indicator is the attenuation value, which describes how much light is lost in a cable. To maintain the required quality standards, it is necessary to closely monitor the production process and try to eliminate any causes for variations.

The improvements in the quality management process in this thesis are focussed on two subjects: First improving the ability of operators to make a distinction between random causes of attenuation variations, which are inherent to the design of the production process and assignable causes of variation, which are caused by parts of the production process functioning incorrectly. Such that they can be corrected in time before quality standards are exceeded. And secondly, delivering an overview of the most likely attenuation causes, while distinguishing between causes in the production process and causes influenced by the measurement process.

Research methods/approach

The method of statistical process control (SPC) helps make the distinction between random and assignable causes, giving operators/managers the ability to timely act on incorrectly functioning parts of the production process before minimum quality thresholds are exceeded. For the current research, SPC will be implemented on the final quality check of the 288-type cables. First, a zero measurement of the process is done to determine the ability of the process to run within its specification limits. Additionally, a zero measurement is done to calculate the share of products not having attenuation issues. Moreover, it is required to find more information about how to implement SPC, so a literature review is done. After that, the measurement system is analysed at the end control to obtain the validity and reliability of the measurement system.

Furthermore, to apply SPC it is required to set up control limits. If the measured values are outside the control limits the cause could be defined as assignable. In such a case it is required by the operator to find causes on the production line itself. Finally, the likely error causes of the production process are identified by making use of a cause-and-effect matrix and a brainstorming session to find the corresponding possible causes and the relation to the various attenuation failures occurring.

Results

The upper control limit when having filtered the results is given in Table 5.3-3. After filtering the attenuation values for failures, the performance values were recalculated, and all values represented a six-sigma process. After having done the brainstorming session and made the cause-and-effect matrix, it was concluded that the four highest scoring causes for attenuation issues are: 'tube length is too small to fit correctly into a cable', 'tube length is too long to fit correctly into a cable', 'the reel core diameter is too small for the specific cable', 'lining out the tubes is not done correctly'. The measurement system for obtaining attenuation values has a relatively high repeatability variation, which means a relatively high percentage of variation due to the measuring instrument itself. It was concluded after conducting another MSA (measurement system analysis)that this was due to the multiple alignment system(MAS) parts.

Discussion of the final result

Only the 288-cable gets taken into account in this research and SPC is only applied to the 288-cable. Additionally for finding causes for the attenuation issues only sheathing line 5 is considered. This is the location where the 288-cable is being produced. This has been done as the 288-cable obtained a high share of attenuation issues. Additionally, the results for the MSA could be somewhat skewed as the products (optical fibres) at which the measurement system was done have all very similar attenuation values. This makes the part-to-part variation a relatively low share of total variation and the other variation causes higher. Additionally, only the upper control limits will be taken into account as having a low attenuation value is not a bad thing as attenuation should be as low as possible. However possible faults in the measuring equipment could be kept unnoticed when only using UCL's

Conclusions

The conclusion could be split up into multiple items. First of all the conclusions concerning statistical process control, furthermore, the conclusions for the root causes for attenuation issues on the production line, and the root causes concerning the measurement system. The current capability and performance values when taking the values for the third measurement and removing outliers are 2.17 for the P_p and 0.73 for the P_{pk}. More explanation about both performance indices is given in section 1.3. Whereas they should lie above 1.5 for the performance indices according to (Theisens, 2016), which results that the P_p is not according to the specification limits.

Making sure the new way of measuring will be maintained over the long term is done by the improved user interface of the optical time domain reflectometer (OTDR) software, and the new control limits. Moreover, it is important to make sure the faulty cables are examined more, this could be realised by taking a sample of failed cables and researching the cause without immediately repairing the cable. The capability of the process to run within its specification limits was not according to a six sigma process. After having filtered the results, and simulating the application of control limits, it was concluded that the application of control limits resulted in the process being able to run better within its specification limits. More information about how the testing of the control limits took place can be found in Section 6.2. The P_p improved from 0.73 to 9.06 and for the P_{pk} from 2.17 to 27.55.

Readers guide

Glossary

Table 0-1. glossary

Abbreviations	Meaning
6 M's	Method, mother nature, man, measurement, machines, materials
AIAG	Automotive Industry Action Group
BPMN	Business Process Model and Notation
CableMES	Cable manufacturing execution system
CTQ	Critical to quality
dB/km	Decibel/kilometre
DMAIC	Define, measure, analyse, improve, and control
FTR	First-time-right
KPI	Key performance indicator
KPIV	Key process input variable
KPOV	Key process output variable
MAS	Multiple Alignment System
MSA	Measurement system analysis
n	Subgroup size equal to 288 fibres
nm	Nanometre
NOK	Not OK
OTDR	Optical time domain reflectometer
SPC	Statistical process control
STC	Soft tube cable
TKF	Twentsche Kabel Fabriek
TKH	Twentsche Kabel Holding
UI	User interface
VMI	Veluwse Machine Industrie

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Contents

1 Introduction

This section depicts a short introduction to the company. Moreover, the problem context gets discussed. As well as previous research related to this subject, carried out at the company gets discussed. The core problem gets determined. The motivation for research as well as an explanation of the company and the respective problems the company is facing will be given. Additionally, to find answers to the problem at hand it is first needed to find answers to the research questions and sub-questions. In Section 1.1 the motivation for the research is given. In Section 1.2 the problem statement is described. The problem cluster and motivation for the core problem are depicted in Section 1.5. Besides, the explanation of the variables used in this research is described in Section 1.3. Additionally, the problem-solving approach for the respective research questions will be given in Section 1.6. Additionally, the thesis structure and the problem-solving approach are displayed in Section 1.7.

1.1 Motivation for research

The research will be carried out at the optical fibre cable production facility. This facility is part of TKF's production facility in Haaksbergen. Various cables get produced on the premises in various production halls. The fibre optics cable production facility consists of multiple production steps being carried out. These steps are needed to process the raw optical fibres and turn them into usable optical fibre cables.

This research is meant to improve the quality of fibre optic cable production. The main critical-to-quality indicator in the production process is the attenuation value, which describes the amount of light lost through a cable. Monitoring the production process and making sure causes for variation in attenuation values are minimised are important aspects to maintain quality standards.

This research could be seen as a follow-up from the research done by another Industrial engineering and management student (Ruiter, 2022). His task was to find out how to implement statistical process control (SPC) on the coating line. This statistical process control is needed for the employees to monitor the process better. It will help the employees be able to monitor the actual process of attenuation measurement rather than only looking at the individual values and assessing if they are according to specification or not. Statistical process control, and indicating if the process is in control or not is not sufficient for the right SPC implementation. It is also required to provide possible causes for the process not being able to run within specification limits to help operators/employees find the causes of potential issues.

1.2 Problem statement

Currently, the attenuation gets measured at the end quality control. If the attenuation is outside the specification limits of the product, the product gets remeasured. If after remeasuring the product is still not within specification limits the product gets taken out of the process and remeasured or repaired. The process of remeasuring by an operator or manager and repairing is a very time-consuming and money-wasting process. To make sure quality is as good as it can be, variation and mean attenuation values for the reels should be as low as possible.

1.3 Concepts and variables used for quantification purposes.

At first, a good indicator for the spread and mean is the FTR (first-time-right) percentage. It is the share of measured values not having any attenuation issues. This means not needing to rework the cable in any way. A low FTR measurement percentage indicates that the spread is relatively high because a part of the measured values is not within the specification limits. This FTR is calculated by using the following equation:

$$FTR = 1 - \left(\frac{number\ of\ cables\ produced\ having\ attenuation\ failures}{total\ number\ of\ produced\ cables}\right)$$

Moreover, good indicators for spread are the process capability index C_p as well as the process performance index P_p. USL and LSL are the upper and lower specification limits respectively. The σ_{within} represents the value of the standard deviation of a group of values that are similar. A subgroup is defined as having 288 fibres. (Theisens, 2016). Equations for both variables are given below:

$$C_p = \frac{specification\ width}{process\ width} = (USL - LSL)/(6 * \sigma_{within})$$

$$P_p = \text{(USL-LSL)}/(6 * \sigma_{overall})$$

P_p compares the process performance to the maximum allowable tolerance. $\sigma_{overall}$ represents the overall standard deviation from the group of data (Theisens, 2016). The C_p is a measure for calculating the variability or spread of the process. To find out if the process is centred correctly ,within its specification limits, it is suitable using the C_{pk}. The C_{pk} is similarly defined as the C_p. But it also considers the location. It returns a value that indicates how close the process is running to its specification limits. Also, it considers the natural variability of the process. The larger the index value, the more the process is capable of delivering products that are within the specification limits. The equation for C_{pk} is given below (Theisens, 2016).

$$C_{pk} = min\{(\bar{X} - LSL)/(3 * \sigma_{within}), (USL - \bar{X})/(3 * \sigma_{within})\}$$

Likewise, the process performance indicator P_{pk} represents the performance capability but takes instead of only the variation also the location into account. So, the smaller the P_{pk} the better the measurement values for the produced product lies at the nominal value. The equation for P_{pk} is given below.

$$P_{pk} = \{(\bar{X} - LSL)/(3 * \sigma_{overall}), (USL - \bar{X})/(3 * \sigma_{overall})\}$$

The lower specification limits for the attenuation are 0.300 dB/km (decibel/kilometre) and 0.185 dB/km for the 1310 nanometre(nm) and 1550 nm wavelengths respectively. Furthermore, the upper specification limits are 0.374 dB/km and 0.224 dB/km for the 1310 nm and 1550 nm wavelengths respectively. (Theisens, 2016). The wavelength numbers correspond to the wavelength of light the OTDR device uses when measuring the attenuation of the fibre.

A process can shift over time. At both sides of the mean the process can shift to 1.5σ. This enables the incorporation of shifts and drifts, while still maintaining six sigma specifications. According to (Theisens, 2016) if the analysis is based on common cause variation only, it is needed to use process capability indices (C_p and C_{pk}). If the data includes special cause variation or data that has been gathered over a longer period, it is needed to use performance indices (P_p and P_{pk}). A visualisation of process capability and performance is depicted in Appendix F.

1.4 Identification of the action problem

The variables are the mean and spread of the attenuation measurement values at the final quality control at TKF. So, the mean is deviating too much from the ideal specifications. Moreover, there is too much spread in attenuation values at end control.

Likewise, the first-time-right percentage is too low. This is an indicator for the action problem: 'high mean and spread in attenuation values'. This first-time-right (FTR) percentage represents the proportion of cables produced that are not containing the following faults: 'step in attenuation curve', 'attenuation is not within specification limits', and 'fibre crack'. All these three failures have something to do with a problem in attenuation values. As during this research, a reduction in attenuation spread and mean is set to be realised, it is important to look at those three failures. The 'step in attenuation curve' failure is defined as the attenuation suddenly dropping. This is caused by macro bending. Due to a certain part of the cable getting squeezed. This can result in a sudden drop in energy resulting in a specific pattern on the OTDR (optical time domain reflectometer) devices' display. More information about the OTDR is depicted in Appenndix D.

The average FTR proportion is 93.89% for the first 42 weeks of 2022 looking at the STC product range. The FTR percentage for several products is lower than the average of 93.89 per cent (adjusted for multiple failures on 1 product) for all STC products that are tested for attenuation. That is why after analysing the results for the failures it was concluded that the most failure-prone fibres are given in Table 1.4-1. The goal value for this FTR is 98% when adjusting for multiple failures per cable.

Table 1.4-1. Cables prone to failures lower than 92 per cent FTR (n=1129; data for 03-01-22/22-10-2022; source: TKF)

MIK	STC			
Type of cable produced	**# cables produced**	**number of failures**	**FTR (not corrected)**	**share of total production**
12x SM G.652.D (1x12)	50	20	60,00%	4,43%
144x SM G.652.D (12x12)	22	6	72,73%	1,95%
288x SM G.657.A2 (24x12)	444	50	88,74%	39,33%
576x SM G.657.A2 (48x12)	24	2	91,67%	2,13%
72x SM G.652.D (6x12)	8	3	62,50%	0,71%
72x SM G.657.A2 (12x6)	11	2	81,82%	0,97%
72x SM G.657.A2 (6x12)	25	4	84,00%	2,21%
96x SM G.657.A2 (16x6)	5	2	60,00%	0,44%

The first-time right ratio for these different fibre types given in Table 1.4-1 is lower than 92 per cent. This is about half of sheathing line 5 production. The other half have FTR values of 92 per cent and higher. That is why it is especially important to have a closer look at the fibres having a high failure rate and subsequently a low FTR share. Also, it is important to look at a cable which is produced in high volumes.

1.4.1 Identification of the norm

Additionally for the process to be six-sigma approved the process must be within three standard deviations from the nominal value(Theisens, 2016). For this to hold the $C_p$and C_{pk} must be bigger or equal to two according to (Theisens, 2016). This is equal to the process fitting twice within the tolerance range. It also gives a specification range of 6σ. Furthermore, the P_{pk} and P_p must be bigger or equal to 1.5 according to (Theisens, 2016). This represents a specification width of 12σ, as the process must fit twice within the specification width. Further metrics for a centred process and a longer-term process with a 1.5 σ shift incorporated are displayed in Appendix G and Appendix H (Theisens, 2016). These norms are obtained directly from (Theisens, 2016). The current performance values will be calculated in Section 4.1. The FTR norm should be about 98 per cent, without correction for multiple failures per cable. This means that in 98 per cent of the cases attenuation measuring takes place without the three failures given. This number has been determined after discussing the FTR with Alfons ten Tije.

1.4.2 Research scope

As there is only so much time to do the research, it is important to focus on the most common cable providing the most revenue for the company. Throughout the research, the focus will be on the soft tube cable (STC) product range. This is the most produced product group at the fibre optics plant. The STC cable type is produced on sheathing line 5. The cable that will be looked at is the 288x SM G.657.A2 (24x12) cable. This cable consists of 288 fibres. The 288-cable contains 24 tubes each containing 12 fibres.

The 288-cable has a first-time-right share of 91.44 per cent when adjusting for multiple failures per cable. This is relatively low in comparison with the average FTR of 93.89 per cent. The FTR, number of failures per product type, and the share of total production could be viewed in Appendix A. The cable's production volume is high in comparison with other fibre optic cables. The production of the 288-cable represents 35.5 per cent of the total sheathing line five production volume and 39 per cent of STC production volume from sheathing line five. Likewise, it represents about half of all failures. That is why the research will be mainly focused on this particular cable.

A table with the produced STC cables with the mentioned failure type is given in Appendix A. It is important to note that those failures are based on the number of failures that get created by the employees in the system. For instance, when a product needs to be cut up when there is a fibre breach then there will exist several extra failures corresponding to the number of products existing from the initial product. When only looking at the original failure the FTR should then be higher. The cables mentioned above are all produced on sheathing line five. Moreover, cables often consist of similar tubes containing similar fibres. It makes it possible to also implement the solution or part thereof on the other cables. As mentioned earlier, due to the high production volume and revenue share it is important to first focus on improving the FTR of this particular cable. When time allows, the improvement implementations could also be implemented on the other given products.

1.5 Problem cluster and motivation of core problem

By making use of Section 1.4, it becomes possible to construct a problem cluster. This problem cluster is needed to derive all problems and their causes. Subsequently, it provides the core problem. The problem cluster is there for finding the core problem that is causing the action problem. The core problem has no known cause itself. The problem cluster is depicted in Figure 1.5-1. When having a look at the problem cluster in Figure 1.5-1. There are multiple potential core problems. The core problem is a problem in the problem cluster not having any known causes or causes that could be influenced (Heerkens, 2017). If and to what extent the problem of an 'inaccurate measurement system' exists is determined by the measurement system analysis, carried out in Section 4.3.

Additionally, for the possible issues and improvements needed on the sheathing line, a brainstorming session with employees will be carried out. The measuring system is only measuring the values individually and is not measuring any kind of trend or range in the measured attenuation values resulting in less knowledge about how the process is behaving in terms of attenuation of the fibres.

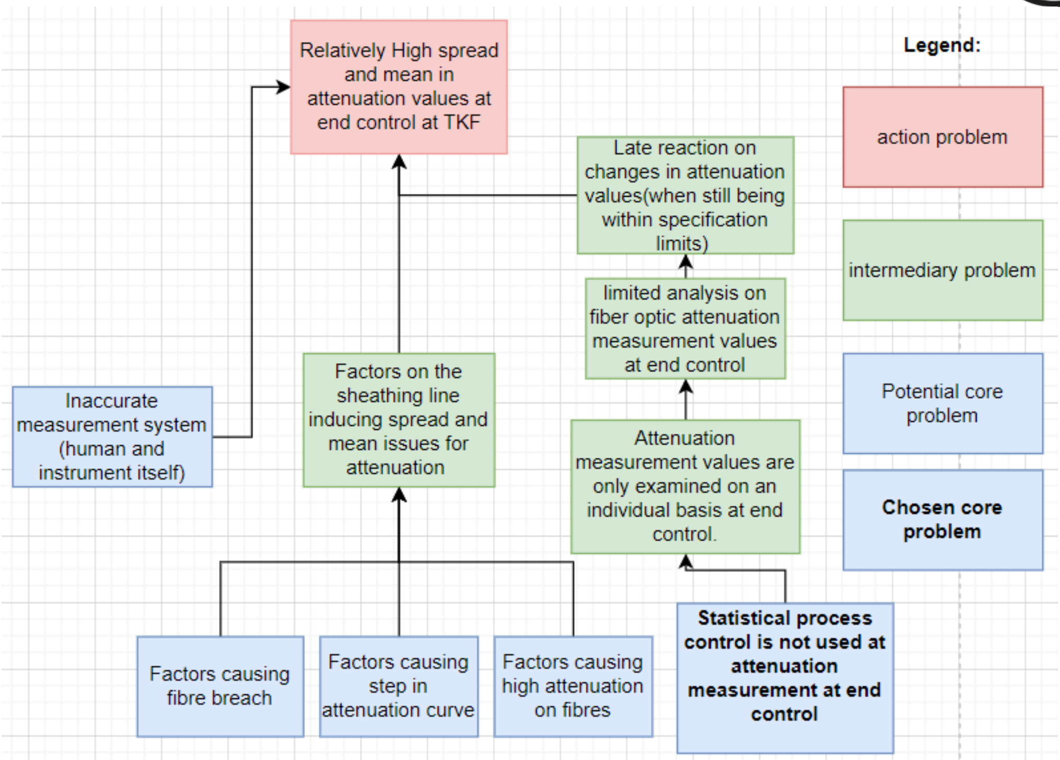

Figure 1.5-1 Problem cluster

1.6 Research questions

The main research question is: 'How to implement statistical process control on the attenuation measuring process at the end control?' This knowledge question is related to the core problem: 'The attenuation values are only assessed on an individual basis'. To find a solution to this knowledge question, it is required to find answers to the following research questions. The sub-questions might be knowledge questions requiring literature reviews. The sub-questions are ordered according to the DMAIC (define, measure, analyse, improve and control) method mentioned in Section 1.7. Before the research questions can be answered, answers need to be found for their respective sub-questions. An overview of the research questions and their respective sub-questions is depicted in Section 1.6.1.

1.6.1 Sub-questions and deliverables/approach for answering the questions

RQ1

'How does the production process look like at the moment?' (define)

- *'What kind of measurements are done for quality control after the individual process steps?'*
- *'How are the optical fibres currently being measured and analysed at the final check and other process steps?'*
- *'What is being done at the individual production process steps?'*

This question will be answered by obtaining information at the optical fibre cable manufacturing plant, doing interviews with multiple employees/operators and finding information for multiple processes. Also, it is essential to find various perspectives on how the production process is working. Additionally, the information will be distributed in process maps.

RQ2

'What are the most important things found in the literature concerning statistical process control? (Literature study)'

- *'What is the historical background and theory behind statistical process control?'*
- *'What control charts should be used for the application of statistical process control at TKF?'*
- *'What is a good methodological method to implement statistical process control at TKF?'*

For this part, a systematic literature review needs to be carried out to provide information about SPC. With that, an analysis of the statistical process measures will be found. Additionally, a certain statistical control method as well as a procedure for statistical process control that can be implemented will be given.

RQ3

'How are the cables currently performing in terms of spread and mean at the end control?' (measure/analyse)

- *'What is the development of the FTR percentage (of attenuation measurement at end control over time)?'*
- *'What are the validity and the reliability of the attenuation measurement system at end control? (analyse)'*
- *'What are the current process capability and performance of the process? (analyse)'*

For determining the performance of the measuring system, it is required to do a measurement system analysis. To find the current capability and performance it is required to analyse the attenuation measurement data from May to November 2022. Additionally, to find the FTR percentage development, it is also required to analyse the data for failures and total production of cables.

RQ4

What are possible implementations to improve the mean and spread for the attenuation values at the end control? (improve)

- *'How can the measurement system (human and system) be improved to realise a reduction in mean and spread for the attenuation at the end control?'*
- *'How can the statistical process control be implemented to improve the spread and mean of the attenuation values?'*
- *'What are the relations between FTR and influencing factors on the production level?'*
- *'What are good control limits for the attenuation measurement process?'*
- *'What production process steps are influencing the high spread and mean at end control the most?'*

After having carried out the measuring system analysis of certain possible measurement system parts (human and system), it becomes possible to derive multiple improvements. Determining the relationship between the attenuation failures occurring and the influencing factors on the production level a brainstorming session, and with the help of employees a cause-and-effect matrix for the influencing factors and the failures occurring from those factors will be developed.
The control limits are determined with the use of Minitab software and the attenuation data.

RQ5

'How to make sure the new way of measuring and analysing the measurements will be maintained over the long term? (control)'

- *'How to implement training for the operators using the new way of analysing the testing data?'*
- *'What are the process capability and performance indices after improvements are implemented?'*
- *'What KPIs are needed to measure the current process performance with respect to attenuation?'*
- *'How to monitor the performance of the proposed changes on the production level to improve spread and mean?'*

For making sure the new way of measurement and SPC implementation is applied, it is required to give recommendations on how to alter the measuring software enabling its use. The process performance indices are calculated using the same data as in the measuring/analysing step, but then when not including the values outside control limits. Moreover, it is needed to find certain KPIs representing the performance in the spread and mean of the process. These KPIs are partly similar to the capability and performance indices used in the measuring/analysing phase.

1.7 DMAIC and thesis structure

The six sigma DMAIC strategy is especially useful when it is needed to find a method for systematic process improvement. Linderman gives the following definition for six sigma: "Six Sigma is an organized and systematic method for strategic process improvement and new product and service development that relies on statistical methods and the scientific method to make dramatic reductions in customer defined defect rates."(Linderman, 2003) By doing this research, quality will improve, and defect rates will be reduced. A figure with definitions of all necessary steps could be viewed in Appendix E (Linderman, 2003). These steps are linked to the research question. As the research questions are used as steps for conducting the research, the research steps are also in the DMAIC form. When solving this problem, the define, measure, analyse, improve, and control method is maintained. The chapter sections and the structure of these chapters are given in Table 1.7-1.

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Table 1.7-1 Thesis structure

Chapter	Phase	Research question	Purpose
2. Current situation at the fibre optics cable production facility	Define	**RQ 1**	Obtaining knowledge about the production process
3. Literature review of statistical analysis methods.	-	**RQ 2**	Obtaining knowledge about statistical analysis methods
4. Current situation quantified	Measure/analyse	**RQ 3**	Doing measurements of the data, and analysing the current process state.
5. Finding solutions	Improve	**RQ 4**	Finding solutions for the statistical assessment of attenuation data, as well as finding attenuation influencing factors on production level and measuring system improvements.
6. Attaining improvements in future	Control	**RQ 5**	Recommendations on how to implement and maintain the new statistical assessment of attenuation data and improvements on the production level

2 Current situation at the fibre optics cable production facility

Chapter two is the first content chapter although, in the first chapter, an introduction about the research is given, in this chapter, an introduction to the company's production processes is depicted. Additionally, there is special attention to the end control and the sheathing process as this research is mainly focused on these two parts.

The information streams and production process for fibre optics cable production is relatively complicated. To give some more insights into the process and its information streams, detailed process maps are given in this chapter. During the define phase process maps from the different process steps will be displayed. The different process steps of the cable manufacturing line are depicted in this chapter. First, the colouring process is described in Section 2.1. Thereafter the coating process is mentioned in Section 2.2. Furthermore, the sheathing and end quality control process gets mentioned in more detail in comparison to the other process steps, since research is mainly focused on those two production steps. This part is shown in Section 2.3. Likewise, the IT systems are given in Section 2.4. To summarize, answers will be found for the following research question.

'How does the production process look like at the moment? (define)'

- *'What kind of measurements are done for quality control after the individual process steps?'*
- *'How are the optical fibres currently being measured and analysed at the final check?'*
- *'What is being done at the individual production process steps?'*

2.1 Colouring line

The (business process modelling notation) BPMN is used to construct the different process maps given (Weske, 2007). The colouring process step represents the first production process step within the optical fibre production facility in Haaksbergen. A flow chart for this process step is given in Figure 2.1-2. A legend for the different symbols used is given in Figure 2.1-1 (Weske, 2007). At first, the raw optical fibre cables come in after the preparation of the cables and the machine configuration process for the various fibres. Thereafter the fibres get coloured. This is only done to provide identification of the various cables. After that, multiple quality measures are taken. The attenuation gets measured. If the product is not according to specification, it gets taken out of the process and a failure procedure takes place. Otherwise, the product will be transported to the Coating line for its next production step.

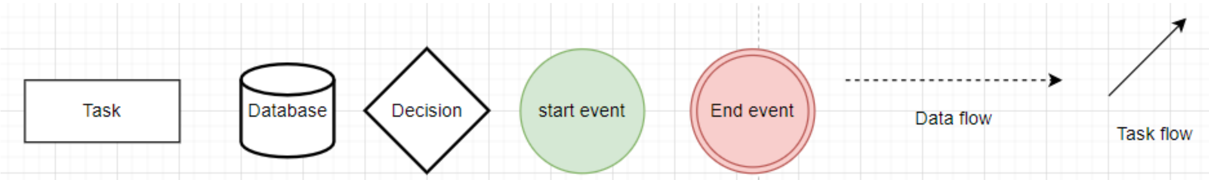

Figure 2.1-1: BPMN symbols

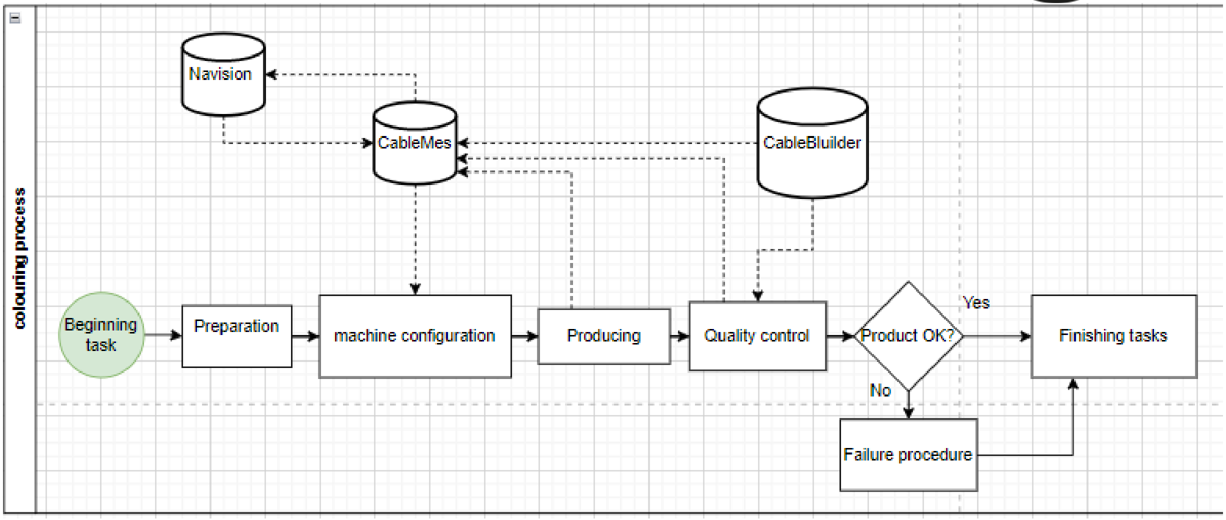

Figure 2.1-2. Colouring process step

2.2 Coating line

At the coating line, the coloured fibre gets fitted together with multiple fibres into a tube. The coating step is described in Figure 2.2-1. The tube is made by making use of an extrusion process. At first, the sheathing line is prepared and the individual products out of which the completed cable consists are put in their place. The machine specifications for the specific tube that is made are loaded onto the machine. When failures occur, certain out-of-control action plans (OCAPs) take place. After the machine configuration step, the production step occurs, and after production, the quality control step takes place, among other things attenuation gets measured again. When all quality requirements are as they should be there is a finishing task, otherwise, first, a failure procedure takes place.

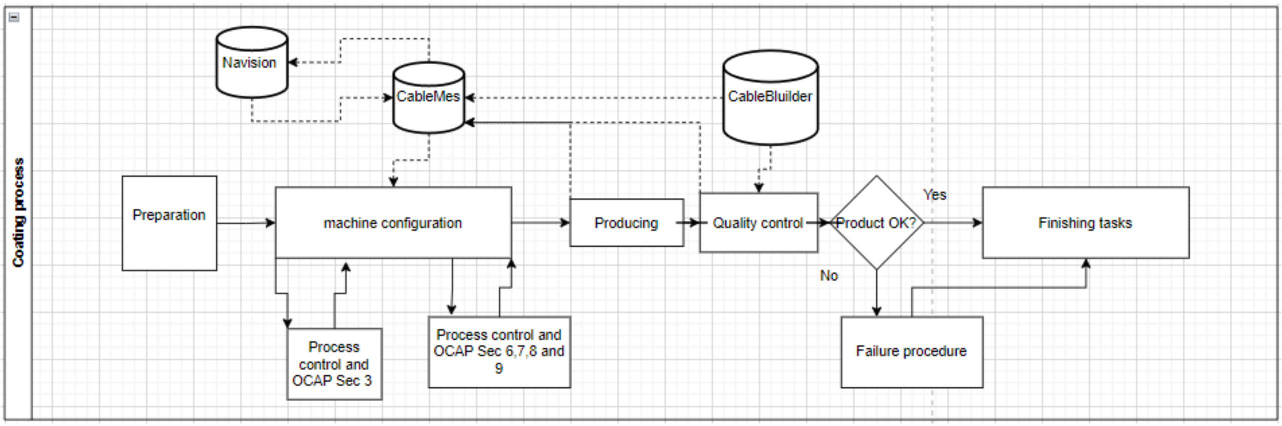

Figure 2.2-1. Coating process step

2.3 Sheathing and end control process explanation

2.3.1 Sheathing production step

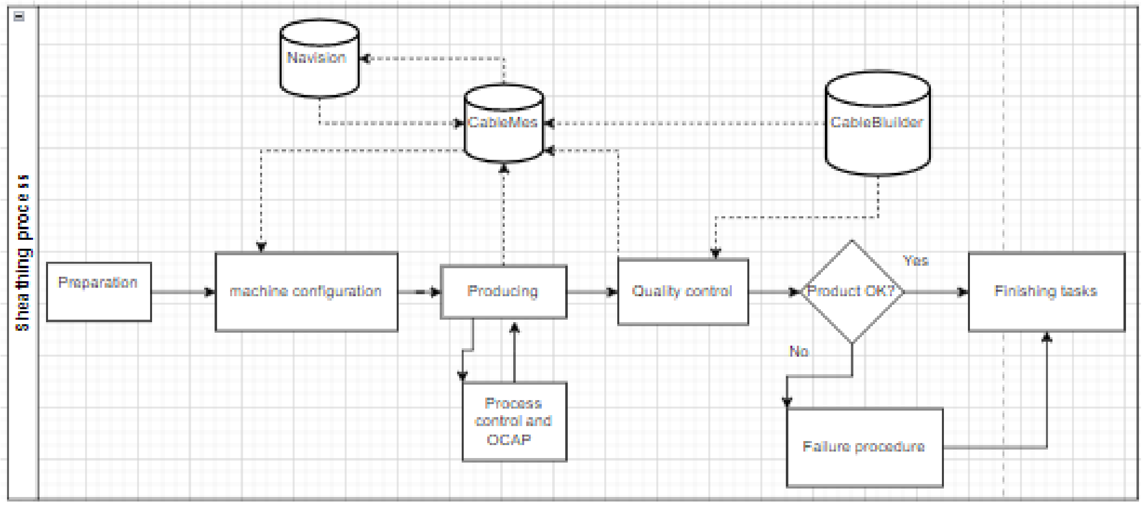

Figure 2.3-1. Sheathing production step

The sheathing process is the final process step in the production of optical fibre cables. This process step provides further protection for the optical fibre cables. The sheathing line is the last production step before the end quality control takes place. The sheathing lines can provide seven types of sheathing procedures. Several parts can be obtained from sheathing line five. The sheathing production step is similarly mapped to the coating production step. As can be seen in Figure 2.3-1.

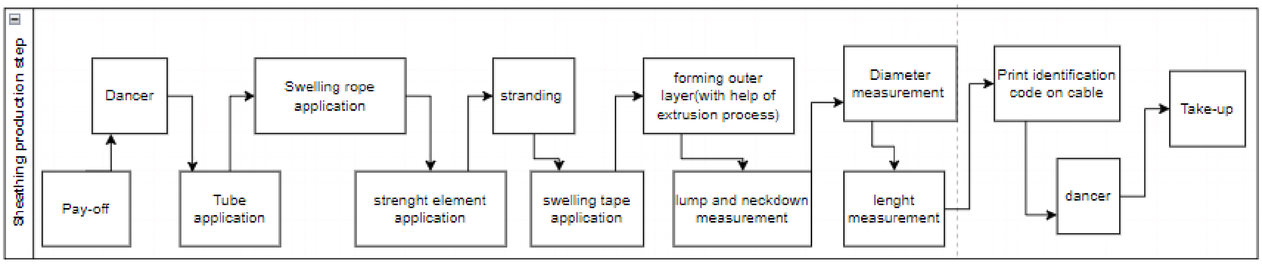

Figure 2.3-2. Sheathing production step

In Figure 2.3-2 the sheathing production step is depicted. This step is a more detailed explanation of the production step in Figure 2.3-1. The physical systems contained in the sheathing line are described as follows. Firstly, there is the payoff. This part of the sheathing line is there to unroll the reel. This element is only there when rewinding needs to take place. During this process step the cable just gets drawn under high tension through the sheathing line and gets put on another reel, while the majority of the systems in the sheathing line are switched off.

The dancer is the next item on the sheathing line. This part is responsible for the velocity at which the reel gets unwound. There is also a place where the tubes get rolled off their respective reel before they will get sheathed and fitted into the cable. Furthermore, the swelling rope gets unwound too. This rope will make sure water is not able to transfer through the cable. The strander is there to make sure the tubes and with that the optical fibres do not fit straight into the cable, making sure they will not get exerted to any forces in the longitudinal direction.

After all, elements got braided together, the plastic layer gets applied in the extrusion process. Later, the cable gets cooled gradually in multiple cooling baths. Furthermore, the cable gets measured on lump, neckdown, and diameter. The length gets measured, and the cable receives an identification print before it gets wound onto a reel. The sheathing protects the cable and its fibres. The aluminium and steel strap armouring provides extra strength on top of the sheathing material. The aramid and the glass yarn provide extra tensile strength. The glass yarn is also used for protecting the cable against animal bites. ("education fibre optics sheathing line theory part 1 ")

2.3.2 End quality control, Attenuation Measuring step.

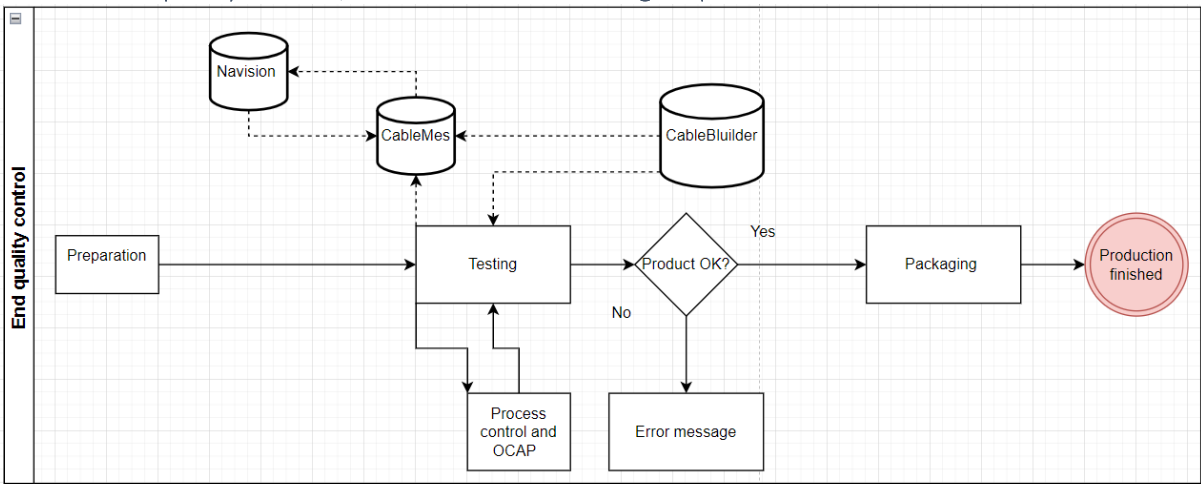

Figure 2.3-3. End quality control step

After the sheathing process, the attenuation gets measured. This is done by using an OTDR measurement system. More details about this system could be found in Appendix D. First, it is important to scan the article number. After that, all details from the cable get downloaded and the order in which the fibres will be measured is displayed. In Figure 2.3-3 a process map of the end quality control step is given. At first, the cables get prepared to facilitate testing. More explanation about the testing and the preparation of the cable before testing is provided in Appendix J. When a certain measuring failure occurs an out-of-control action plan starts. When the product is within specifications the products get packaged and the products get fixed. When the product is not as it should be an error message occurs and the operator needs to begin a failure handling procedure, this involves remeasuring or repairing the cable.

2.3.3 Quality Control KPIs

The aspects that get measured could be viewed as critical to quality (CTQ) aspects. In this case, the critical to quality (CTQ) attributes are mainly related to the product specifications. CTQs for optical fibre cables are the diameter, the tensile strength, and the attenuation. At the colouring line, the fibres get measured on colour, length, printed mark, winding quality, outside diameter, and attenuation. At the coating line the attenuation, diameter, length, and winding quality get measured. At the end control or after sheathing line five the tensile strength gets tested, as well as the attenuation under various conditions. Things that get measured at the sheathing lines are the diameter, length as well as quality of the printed mark. Moreover, the printed marker quality gets tested.

2.4 Production process and its IT systems.

The databases depicted in Figure 2.1-2, Figure 2.2-1, Figure 2.3-1, and Figure 2.3-3 will be discussed in this section. The information about what cables need to be produced and the components in the (sub)products comes from Navision. This is an enterprise resource planning system. This software system keeps track of the stock, orders, and ordering of raw materials gets done through this system.

Cable Builder is cable design software. For every product, it stores certain quality metrics. For instance, the maximum attenuation values, as well as the maximum and minimum dimensions a cable, or intermediary product should have. CableMES (cable manufacturing execution system) is specifically designed for the cable manufacturing industry. TKF is currently in the phase of introducing this software system through the whole fibre optics cable manufacturing plant. Through CableMES an operator can scan a certain (sub)product and can directly derive the right information about the product from cable builder and Navision. Information like, what tension various sub-products and raw materials need to be put into the produced product, what materials are needed to produce the product, and on what machine, under what machine settings it should be running.

CableMES functions as an intermediary between the operator, Navision, and CableBuilder. It is the main software tool the operators use for making a certain product, doing measurements, and reporting back when failures occur. CableMES also provides very good monitoring capabilities for managers. It tracks for instance how long a machine is running, at what speed it is producing, what it is producing, and any operational issues, and gives insights into the measurements being carried out. Additionally, it provides updates to the stock level in Navision. Providing for instance Navision triggers to order more of certain products.

Also, CableMES can obtain quality measurement information like attenuation values and diameter values. From CableBuilder (cable design software) CableMES can acquire the correct specifications for these CTQ attributes for certain (sub) products. Thereafter CableMES can check if the CTQ measures obtained from the OTDR software, are within the limits provided by CableBuilder. The program is, if needed, able to quarantine a certain (sub)product automatically when one or multiple CTQ measures are not as they are supposed to be.

The databases: Navision, CableMES, and CableBuilder are all responsible for the data needed for the machine configuration, production, and quality control process. Also, the data stored in Cable Builder and Navision is needed for the end control. Comparably, the testing results will get stored in CableMES after doing all quality checks at end control.

2.5 Concluding remarks

This chapter depicted information about the fibre optics cable production facility. It provided a process map for the individual processes. It also provided information about the attenuation measuring process at the end control. Answers to the (sub) questions were found and could be viewed below.

‘What kind of measurements are done for quality control after the individual process steps?’

The following measurements are done at the individual process steps:

At the colouring line, the fibres get measured on colour, length, printed mark, winding quality, outside diameter, and attenuation. At the coating line the attenuation, diameter, length, and winding quality get measured. At the end control or after sheathing line five the tensile strength gets tested, as well as the attenuation under various conditions. At the sheathing lines are the diameter, length as well as quality of the printed mark.

'How are the optical fibres currently being measured and analysed at the final check?'

At the final check, the attenuation gets measured with the use of an OTDR and a MAS system. This makes it possible to semiautomatically measure the fibres contained in a cable for attenuation. It is required to make use of different Databases: CableMES, CableBuilder and Navision to be able to find the specification of the various cables and check if they are correct or not.

'What is being done at the individual production process steps?'

The production of optical fibre cables from a raw optical fibre is done through 4 process steps. Colouring, coating, sheathing and end quality control. The individual process steps could be found in 2.1, 2.2, and 2.3.

3 Literature review

3.1 Introduction

An introduction about the processes and its IT systems as well as the quality measurements done at the fibre optics plant was given in Section two. In this section, an introduction to statistical analysis methods will be given, with the help of literature supporting it. In Section 3.2.1 a general introduction to SPC is given. In Section 3.2.2 an introduction to control charts is given. In Section 3.2.3 a methodology for applying SPC is depicted. In 3.3 a further analysis of choosing the right control chart is made. Additionally, information is provided to calculate control limits. During the literature study, more information about SPC is acquired. Full documentation of the search could be found in Appendix C. Answers will be found for the following research questions.

'What are the most important things found in the literature concerning: statistical process control?' (analyse)

- *'What is the historical background and theory behind statistical process control?'*
- *'What control charts should be used for the application of statistical process control at TKF?'*
- *'What is a good methodological method to implement statistical process control at TKF?'*

3.2 Literature review about SPC

3.2.1 Introduction to SPC

Statistical process control is a methodology that uses statistical techniques to monitor and control a process. It involves measuring and analysing the performance of a process over time and using statistical methods to determine whether the process is operating within acceptable limits (Pyzdek, 2014). The roots of SPC can be traced back to the late 1920s. Walter Stewart was working as a statistician at AT&T Bell laboratories to improve the product manufacturing equipment. After that, it was used in post-World War II Japan. W. Edwards Deming helped distribute Statistical process control over the whole world. Stewart and Deming originally applied SPC to manufacturing processes. But later on, realised SPC could be applied to any sort of process, where repeated measurements are taking place. (Vetter, 2019)

The goal of SPC is to help organisations identify and eliminate sources of variability in their processes, realising improvement in quality, efficiency and eventually customer satisfaction. Process monitoring is used to identify when the process is running within or outside its normal variability range.

An important aspect of SPC is its' support in the continuous improvement of process performance. It is used by organisations that are striving for a high level of quality and efficiency in their operations. This improvement is realised by constantly reducing the unexplained variability. (De Vries, 2010). Variation in the production process is normal, but the causes could be split up. Causes are split up into chance causes and assignable causes. Chance, random, or common causes of variation are not able to be repeated, due to the natural variation occurring in a production process. This might be due to for instance materials or operating conditions (Vetter, 2019). Assignable or special causes of variation are causes of variation that can be identified and could be linked to particular causes.

A process that is running with assignable causes is defined as a process that is out of control. Once those causes are identified and appropriate action is taken to eliminate these causes of variation, the process will be running back into control (Vetter, 2019). A control chart monitors the variability of the process. A control chart is applied to observations or data over time indicating if a process is running as it should be. Control charts have upper control limits and lower control limits. (De Vries, 2010)

3.2.2 Control charts

Control charts are used for statistical regulation in the process. They can distinguish between random and systematic causes. So when using control charts the main goal is to improve and regulate the process quality (Gejdoš, 2015). For instance, they could be useful when a reduction in the variability of the process, as well as an improvement of the mean, is necessary. The horizontal axis of a control chart contains when statistical sampling, or (on an individual basis) a certain measurement took place. The vertical axis contains values of the calculated sample characteristics (Gejdoš, 2015). When the observations from a process could be grouped in groups of at least four observations and the observations are continuous the Shewhart $\bar{X}$ charts could be used. This chart is used to monitor the central tendency. The standard deviation should be calculated from the data used within the subgroup.

The costs of both type I and type II errors are relatively difficult to derive and mostly not known within organisations. That is why the control limits could be set three standard deviations from the mean. Setting the control limits at three standard deviations from the mean is set to be appropriate for most kinds of distributions with an acceptable number of false alarms. However, when setting the control limits this way could result in poor performance. This is especially the case when unplanned changes are costly and need to be detected quickly (De Vries, 2010).

3.2.3 Methodology and procedures for applying SPC

SPC is an important statistical methodology. It is not there to improve the product quality for the customer directly, but it is initially used for monitoring if the process is in control and optimizing the actual process. This is done by making use of statistical control charts. The control charts themselves do not indicate what is wrong with the process. They are only indicating that the process is statistically in or out of control. Using SPC will result in being able to react before a product is out of the specification limits. This will enable a company to counteract waste. (Antony, 2003)

There are some prerequisites for successful SPC given in (Antony, 2003). These prerequisites are split up into four parts and include management issues, engineering skills, statistical skills and teamwork skills. When considering all company-specific parts a conceptual framework for the implementation of SPC could be made. This framework is given in Appendix B. Most points in the framework are useful, but some are evident and do not need to be further addressed. Also, it is not possible to have a clear cost-benefit analysis. The process prioritisation for SPC studies is important and this prioritisation is well established within the company.

This study mainly addresses how SPC could be implemented in the general quality management processes within the company. Also doing an MSA is an important step. This has been done in the measurement phase of this report in Section four. The construction of control charts is also an important step. In section 3.3 some useful control charts are selected for this research. The calculation of the control limits will be done in Section 5 during the improvement phase of the project. When the process is not in control, an OCAP has to be done. In Section 6 during the control phase, an OCAP is given. Moreover, in Section 4 the performance of the process is calculated.

3.3 Choosing the right control charts

As it is important to improve the mean and spread of attenuation values, control charts related to measuring those values should be introduced. For instance, it is important to take a control chart that gives control values for the range. Additionally, the central tendency or the ability of the process to run within its' control limits. In Figure 3.3-1 it could be obtained what control chart needs to be used when having various circumstances as given(De Vries, 2010) (Theisens, 2016). The letter n represents the subgroup size.

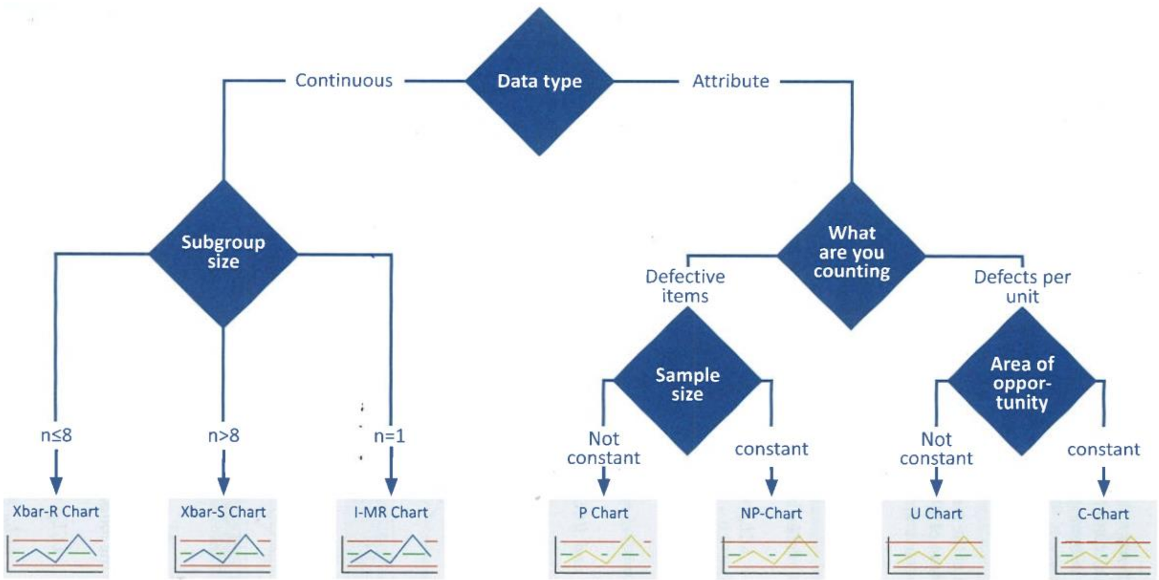

Figure 3.3-1. Choosing the right control chart

As the attenuation values are continuous, it is required to exclude the p, u, np and c charts immediately. Additionally, the SPC will only be carried out on the 288-cable. This means that the subgroup consists out of 288 fibres. N represents the subgroup size in the figure. So, the only available chart is the Xbar-S chart.

When using an Xbar-R chart the plotted range is the sample range. Once having large samples, the range value becomes larger. Because the probability of having more outliers increases with the increase in sample values. When assessing those outliers, the range becomes very large and is not representing the variability of the sample. When using the sample standard deviation, the variability of a larger sample is assessed better because all values contained in the sample are considered, instead of only the largest and smallest values on the range chart. The Xbar chart plots the mean of the subgroups. Together with the mean it also plots the subgroup standard deviation of n subgroups. The centre line represents the mean of all subgroups and the total standard deviation. Action needs to be taken if the subgroup mean values is passing the Xbar control limit and/or if the subgroups sample standard deviation crosses the S-charts control limits.

Calculating the control limits

The control limits could be calculated by making use of MiniTab. However, it is useful to derive the theoretical background with respect to calculating these limits. When using an Xbar-S chart it is needed to use the following equations(Theisens, 2016).

$$LCL_X = \bar{\bar{X}} - A_3 * \bar{s}$$

$$UCL_X = \bar{\bar{X}} + A_3 * \bar{s}$$

$$LCL_S = B_3 * \bar{s}$$

$$UCL_S = B_4 * \bar{s}$$

With LCL_X and UCL_X representing the lower and upper control limits respectively for the subgroup mean used when making an X-bar chart. The LCL_S and UCL_S are representing the lower and upper control limits for the subgroup standard deviation, used when making a S-chart. $\bar{s}$ represents the mean standard deviation of all subgroup's standard deviations. $\bar{\bar{X}}$ is the mean of all subgroups means. This represents the centre line of the Xbar chart.

The values forA_3, B_3 ,and B_4 can be found in a statistical table. This table provides values for A_3, B_3 ,and B_4 based on subgroup size. However, the subgroup size is larger than the maximum subgroup size of 25 used in the table provided in (Theisens, 2016). That is why the table needed to be extended. This is done by making use of multiple equations. The subgroup size at TKF is 288 for the 288-cable. An extended table for the constants used in the control limits' equations can be found in Appendix N. Also the equations("Xbar and s control chart," 2021) used for calculating those constants are provided in Appendix N.

3.4 Concluding remarks

To conclude this section short answers for the sub questions will be given.

What is the historical background and theory behind statistical process control?'

Statistical process control is a methodology that uses statistical techniques to monitor and control a process. It involves measuring and analysing the performance of a process over time and using statistical methods to determine whether the process is operating within acceptable limits (Pyzdek, 2014). The roots of SPC can be traced back to the late 1920s.

What control charts should be used for the application of statistical process control at TKF?

For the current process of measuring attenuation values, it is required to use an X-bar-s chart with a subgroup size of 288.

What is a good methodological method to implement statistical process control at TKF?

A methodology for implementing SPC is found in Appendix B.

4 Quantification of the current situation

In Section two the current production situation is explained. Whereas in this section the variation in attenuation values is quantified using the variables that got introduced in Section 1 and control charts that got introduced in Section three. Also an introduction about the OTDR is given in Appendix D providing more information about the system behind doing the measurements. Additionally, the measurement system gets analysed, and the performance of the measurement system will be determined in this section. In Section 4.1 the current performance of the process gets determined. The focus will be on the 288 fibre-containing cables. In Section 4.2, the first time-right development of the failures occurring over time will be analysed. In Section 4.3, a measurement system analysis is introduced and conducted. Being concrete, answers will be found for the following research questions.

How are the cables currently performing in terms of spread and mean at the end control? (measure)

- *'What is the development of the FTR percentage (of attenuation measurement at end control over time)?'*
- *'What is the validity and the reliability of the attenuation measurement system at end control?'*
- *'What is the current process performance?'*

4.1 Current performance

4.1.1 Testing if data is following capability and performance calculation requirements.

To calculate the performance and capability of the process the data needs to adhere to some requirements(Theisens, 2016). First, it is needed to make sure the data is stable. To test stability in the process, it is required to use a Run chart. Every run corresponds to a transition in mean from 1 288 fibre-containing cable to the next measured 288 fibre containing cable. This chart is used to determine if any special causes are influencing the process. A run chart of the attenuation values is given in Figure 4.1-1 (Theisens, 2016). This chart plots the sample means of the 288 type cables being measured at end control from old to new. It also provides the individually measured attenuation values as the light grey dots.

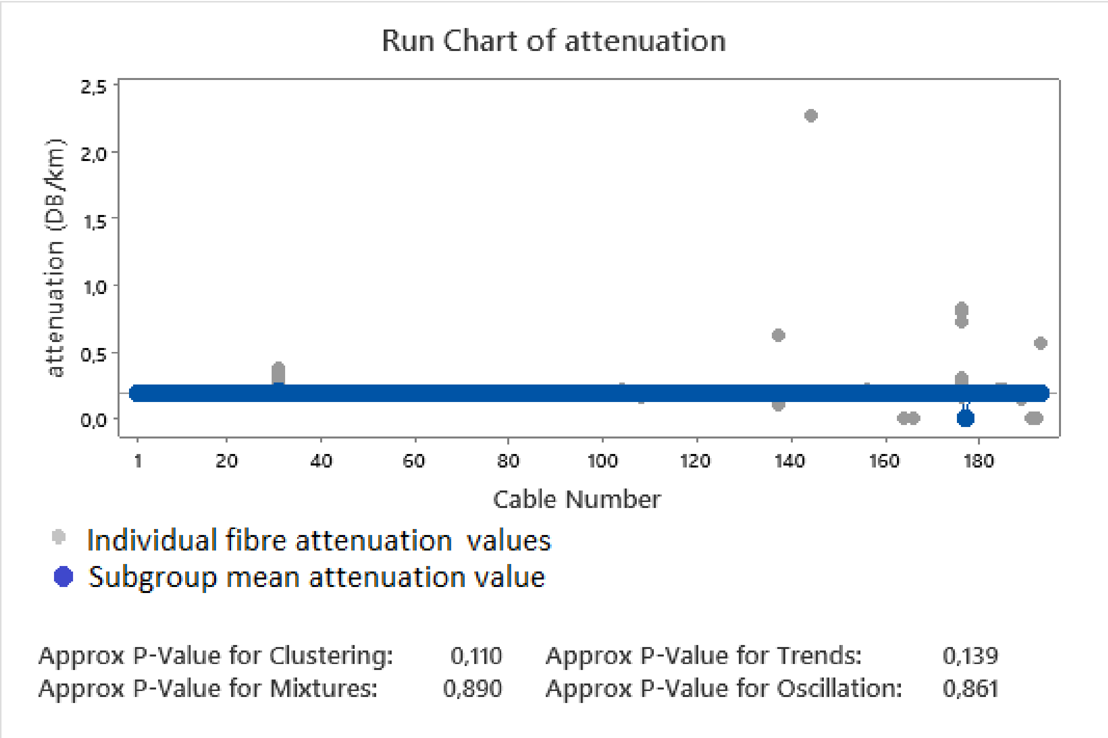

Figure 4.1-1. Run chart of mean attenuation (n=55584; T=12-05-22/12-01-23; Source: TKF)

This test evaluates if the process has special non-random patterns. Patterns include clusters, mixtures, trends, and oscillations. Clusters are data points having similar characteristics and not having data points evenly distributed over the whole measuring range. Clusters may indicate problems like measurement problems, lot-to-lot, or setup variability. Mixtures are patterns that result in the crossing of the centre line of the data on multiple occasions. When having multiple datasets, there is a probability of obtaining behaviour like this. Trends are certain drifts in the data, when the trend keeps on going the data might get out of control. Oscillating patterns are patterns in the data indicating that the process is not in a steady state.

To calculate the capability and performance the data needs to be clear of any non-random patterns. The null hypothesis is set to be: ‘the data observed is not attributed to special causes’. If the p-value is lower than 0.05 one could conclude that the null hypothesis needs to be rejected. As all p-values are bigger than 0.05 it is not allowed to reject the null hypothesises, so the data variation is not due to special causes (Theisens, 2016).

Additionally, it is required for the data to be normally distributed when conducting a capability analysis. A Goodness of Fit Test is carried out in MiniTab. With this test, it is possible to find out how the data is distributed. When the p-value for a certain distribution on the data is higher than 0.05 the data fits the distribution. In this case, every p-value is lower than 0.05, hence no distribution fits the data. Although the data is not normally distributed, it will be assumed that it is, and the capability and performance indices will be calculated accordingly. This has been decided after consulting the company supervisor. Moreover, the difference between the current, and the situation after improvements have been made will be calculated. Then the distribution of the data is of less importance.

The capability and performance could be deduced from the data of attenuation values. The summarized attenuation data from all OTDR measuring systems get stored and written down in an Excel file. After that, the data should be split up. This is needed to calculate the capability and performance indicators for the various product types. A Minitab report for the cable with identification 288x SM G.657.A2 (24x12) is given in Appendix L. As the data is measured over about 7 months it is required to use the performance indices to assess the process. It is not allowed to use the capability indices for such a long term.

In Table 4.1-1 the current performance indices for the attenuation measurement process at end control are given. The process performance indices are given for the 1550 nm wavelength. The attenuation values are given in dB/km. The upper specification limit for the attenuation when having light pulses with a wavelength of 1550 nm is 0.224 dB/km.

4.1.2 Explaining results

When having a look at the process capability and performance report, it is not needed to consider the observed/expected values below the LSL (lower specification limit) when assessing the fibres for attenuation. It is not possible to have an attenuation value which is negative meaning there is an increase in light when traveling through the cable. Although when having a strangely low attenuation value, the measurements of attenuation are not done correctly, because every fibre must have a certain drop of light energy. It is important for the P_{pk} and P_p to be bigger than 1.5.for the process to adhere to six sigma specifications. These values are depicted in Appendix G and Appendix H. When the process has at least these values for the performance indices, the process is according to six sigma and contains less than 3.4 faulty parts per million (Theisens, 2016).

The $P_{pk}$and P_p are not bigger than 1.5. These values are given in Table 4.1-1. So also, the P_{pk} and P_p have not the requirements of a six-sigma process. More explanation about how the performance and capability indices are calculated could be found in Section 1.3. As the data that is used is given over a longer period it is required to use the process performance indices. When the subgroup size and sample become very large, it is less accurate to calculate the capability indices. The short-term standard deviation gets approximated then. This is done by making use of a statistical table.

In the table it is determined that the inclusion or exclusion of outliers have a big influence on the performance indicators. Additionally, the third measurement is used to make sure the probability of the subgroup size to be 288 is the highest, representing the third measurement without taking into consideration the attenuation values on a cable after reworking procedure took place.

Table 4.1-1. Performance and capability indices for current situation (T= 03-05-22/12-01-23; source: TKF)

Number of fibres (n)	#fibers	Specification limits	With failures	outliers [1]	Wavelength(nm)	Measurement Number	P_p	P_{pk}
80469	random	0 - 0.224	Yes	Yes	1550	3	0.11	0.01
55872	288	0 - 0.224	Yes	Yes	1550	3	0.60	0.20
55584	288	0 - 0.224	Yes	No	1550	3	2.17	0.73
49536	288	0 - 0.224	No	No	1550	3	14.79	4.55

[1] Outliers correspond in this context to one of 194 cables, containing a lot of strangely high attenuation values in the corresponding fibers.

As one is able to recognize when only filtering out the outliers and taking the third measurement containing 288 fibres, the P_p is above 1.5 and the P_{pk} is about 0.73. meaning that only the P_{pk} is not within the limits of a six sigma process although the P_p is.

4.2 FTR development

A second indicator to obtain the performance of the process is the FTR development. It is the percentage of cables not having any failures attributed to attenuation issues. When obtaining a significant change in FTR percentage through time, causes should be determined. In Section 4.2 the development gets determined and conclusions will be drawn to look further into events that happened indicating certain possible significant changes in FTR percentages.

For both figures: the blue line indicates the FTR on a weekly level. The purple line corresponds to the moving average of the FTR, calculated by using the failures and production volume from all weeks before that certain week. The green parts correspond to the number of good products and the red bar represents the number of products containing attenuation failures. The left y-axis corresponds to the cable production numbers. The right y-axis is FTR moving average. The X-axis represents the time in weeks.

A graph of the FTR development could be viewed in Figure 4.2-1. And Figure 4.2-2 represents the development of the 288-cable. There has been a certain development in the FTR percentage over the past year. During weeks 31 and 32 there was no production, so the moving average FTR during these weeks stayed the same. When consulting the development of the FTR over the given failures, it is concluded that a certain pattern is visible. Week 36 contains a high FTR. Also, weeks 16 to 18 contained a lot of failures although the moving average FTR has been trending upwards.

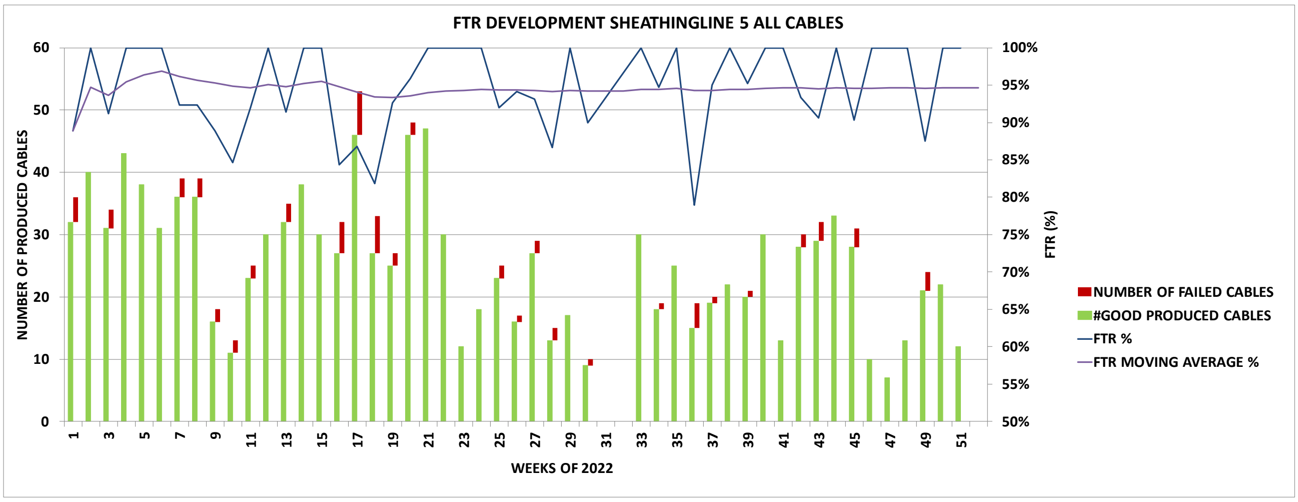

Figure 4.2-1. FTR DEVELOPMENT OF ALL CABLES PRODUCED ON SHEATHING LINE 5(n=1315; data for 2022-01/2022-12; source: TKF)

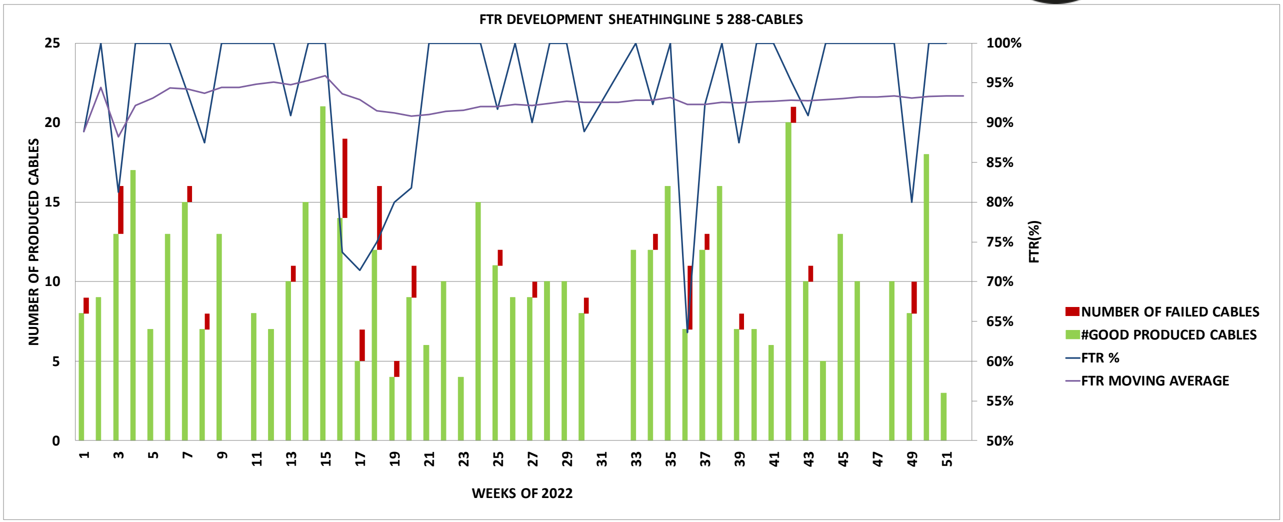

Figure 4.2-2. FTR DEVELOPMENT 288-CABLE (n=526; data for 2022-01/2022-12; source: TKF)

The FTR development for the 288-cables has some correlation with the FTR development of all cables produced on sheathing line 5. It was concluded that the FTR moving average as well as for the individual weeks is relatively high at the beginning of the year meaning that certain failures did not occur that often. From week 16 till week 20 there were a lot of failures resulting in a decrease in FTR values. From week 21 onwards the moving average FTR is slightly rising, meaning that the number of failures as a percentage of the whole production is decreasing. The moving average FTR for the 288 cables is 93.3% at the end of 2022. Meaning that the 288 cable has a lower FTR share than the overall production on sheathing line 5. After having had an interview with some quality improvement employees, there has been no clue found in what exactly happened during the weeks, FTR was significantly lower than the other weeks.

4.3 Measurement system analysis

In Section 4.1 the capability and performance of the process got calculated. In Section 4.2 the FTR development got determined. In Section 4.3 the measuring system itself and variability due to the measuring system (both human and the measuring instrument) gets determined. This involves doing multiple measurement system analyses.

4.3.1 Introduction MSA

A measurement system analysis is required to obtain information about the performance of the measuring system and gives insights into what variability of the values is due to the variability that is obtained by the measuring system (both human and system, and its interaction). (Theisens, 2016). When doing a measurement system analysis, it is required to make use of the rule of thumb: The number of operators multiplied by the number of measured parts should be 15 at minimum(Theisens, 2016). The total variation that gets observed consists of the measurement variation as well as the process variation:

$$\sigma^2_{overall} = \sigma^2_{observed} = \sigma^2_{process} + \sigma^2_{measurement\ system}$$

In this part, the measurement variation gets determined. When having a look at the measurement system it is required to take a look at indicators. These indicators quantify the measuring performance of the system. It represents the magnitude to which the system is able to measure what it is supposed to measure. All variables that enable good measurement system performance are described extensively in 4.3.2.

4.3.2 Indicators for determining the measurement system's performance.

- '%Tolérances' or '%P/T' (p/t ratio)(Theisens, 2016)
  - The percentage of variation due to the source compared to your specified tolerance range.
    - It indicates how well the data lies between the specification limits.
- '%Study variation or R&R' (Theisens, 2016)
  - The percentage of variation due to the various measurements. It is the sum of the variation that can exists from the operators(reproducibility), and the physical measurement system (repeatability).
- '%Contribution' (ratio of the sum of squares) (Theisens, 2016)
  - The contribution in the variation of the various measuring system parts: like the operator, part-to-part, repeatability, and reproducibility.
    - Part-To-Part represents the variability due to measurements of various parts. (When this value is high, there is a lot of distinguishing between the measured parts.)
    - Repeatability is the share of total variation due to the measurement device. It is the variation that is observed because of the variation in the measurement system. This variation is the variation that comes from measuring the same product many times on the same measurement system by the same operator.
    - Reproducibility is the variation that occurs when there is variability in the measurement values from operator to operator.
    - Total Gage R&R represents the sum of the repeatability and the reproducibility components.
  - All different categories should lie under 5% except the part-to-part contributor.
- Discrimination index (it represents to what extent the measuring system contains the right scale to measure) (Theisens, 2016)
  - Is represented by the number of distinct categories.
  - Should be higher than seven.

4.3.3 AIAG (automotive industry action group) gage acceptance standards

To interpret the results from the measurement system analysis that will be carried out the values given in 4.3.2 will be compared to the AIAG acceptance standards. The AIAG acceptance standards are given in Table 4.3-1(Theisens, 2016).

Table 4.3-1. AIAG acceptance standards

Automotive Industry Action Group Suggestions			
% Contribution	% Study Var	% Tolerance	System is...
1% or less	10% or less	10% or less	Acceptable
1% - 9%	10% - 30%	10% - 30%	Marginal
More than 9%	More than 30%	More than 30%	Unacceptable

4.3.4 MSA experiment steps needed to undertake.

There are 3 operators, every operator measures the same 12 fibres and repeats this 2 times. This enables the calculation of the variation due to the measuring system, the different operators measuring, and the operator-part interaction. In Sections 4.3.1, 4.3.2, and 4.3.3 the measurement system gets introduced and the variables are introduced. In the following Sections of 4.3, the MSA steps needed to do for the actual experiment and the description of the results are depicted. First, it is important to make sure the various fibres are all separated and labelled. It is required to place the fibres in the OTDR machine in an order that is maintained when switching round and operators. This order is based on the placement of the fibres in the tube. Placement of the fibres in the MAS will be performed by the various operators separately.

Additionally, the fibres are selected in such a way as to make sure there is a somewhat average sample size. This sample size should be representing the various fibres being measured, with quite some spread in the distinct attenuation values. Due to time constraints, it is not possible to measure a lot during the measurement system analysis. That is why it is required to only measure 12 fibres contained in one tube. These fibres will be measured by three employees. Additionally, every employee will measure the selected fibres two times. The various measurements from the MSA are saved and labelled for measuring round and employee numbers.

4.3.5 Results

After conducting the MSA it is derived that the repeatability is not as it is supposed to be. The repeatability is contributing about 80 per cent to the total variation of the system. This means that variation due to the measurement system itself, when all conditions are the same, contributes to most of the measured variability. Whereas part-to-part is contributing about 20 per cent to the total variation. According to the AIAG, the contribution in variation should be under 10 per cent for the individual measurement system parts, when not taking into consideration the part-to-part variation. Having a high contribution in variation from part to part is a good thing in comparison with other contributors like reproducibility or repeatability. The results of this study are given in Figure 4.3-1. A more detailed explanation could be found in Appendix K.

One of the reasons repeatability is that high is because there was a high variation in attenuation measurement results from the second ninth and tenth of the 12 fibres. When measuring that fibre only a part of the attenuation along the entire length of the fibre was measured, because this fibre included a nonlinear attenuation curve, the attenuation could only be measured on a certain part of the fibre where the attenuation was reducing stably. This is a software error that came to light during this MSA. The people in charge of quality expected the software to calculate the difference in energy at the beginning of the fibre and the energy at the end of the fibre. This is only the case when there is a stable attenuation curve without steps. The fibre was not measured during all measurements on that same piece of fibre length. This resulted in a high spread of attenuation values.

Gage R&R

Variance Components

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0,0002106	79,58
Repeatability	0,0002106	79,58
Reproducibility	0,0000000	0,00
Operators	0,0000000	0,00
Part-To-Part	0,0000540	20,42
Total Variation	0,0002646	100,00

Process tolerance = 0,074

Gage Evaluation

Source	StdDev (SD)	Study Var (6 × SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	0,0145112	0,0870671	89,21	117,66
Repeatability	0,0145112	0,0870671	89,21	117,66
Reproducibility	0,0000000	0,0000000	0,00	0,00
Operators	0,0000000	0,0000000	0,00	0,00
Part-To-Part	0,0073497	0,0440980	45,18	59,59
Total Variation	0,0162663	0,0975977	100,00	131,89

Number of Distinct Categories = 1

Figure 4.3-1 Minitab Gage R&R Results (n=72; data for 13-12-2022; source: TKF)

4.3.6 Results when filtering out fibre 2,9 and 10

The results for attenuation when taking out measurements: 2,9 and 10 are given in Figure 4.3-2. A visual comparison of the results for the different operators is given in Appendix K. Still, the repeatability next to the 'part-to-part' is the main contributor to variation in attenuation. The individual contributors should be less than 10 per cent responsible for the attenuation variation. Also when having a look at the Gage evaluation the tolerance for individual values should be less than 30 per cent. The contribution to the fact that the process is not able to run outside the specification limits is mainly down to the part-to-part variation as well as the repeatability. The discrimination should be more than five according to the AIAG. In this study, the discrimination is two. This means that there are only two distinct categories. This means the scale is not correct to measure the values that it is measuring.

The reproducibility component for the contribution to attenuation is low. This means that the part-to-part interaction is a very small portion of the total variation. The variation existing from the individual operators measuring is also very low in comparison with the part-to-part variation and the variation due to repeatability.

Gage R&R

Variance Components

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0,0000135	28,73
Repeatability	0,0000135	28,73
Reproducibility	0,0000000	0,00
Operators	0,0000000	0,00
Part-To-Part	0,0000335	71,27
Total Variation	0,0000470	100,00

Process tolerance = 0,039

Gage Evaluation

Source	StdDev (SD)	Study Var (6 × SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	0,0036729	0,0220373	53,60	56,51
Repeatability	0,0036729	0,0220373	53,60	56,51
Reproducibility	0,0000000	0,0000000	0,00	0,00
Operators	0,0000000	0,0000000	0,00	0,00
Part-To-Part	0,0057853	0,0347120	84,42	89,01
Total Variation	0,0068527	0,0411165	100,00	105,43

Number of Distinct Categories = 2

Figure 4.3-2. Minitab gage r&r when leaving out fibre 2,9 and 10 (n=54; data for 13-12-2022; source: TKF)

4.3.7 Researching the cause of low repeatability.

From the MSA was concluded that the repeatability contribution towards variation is not acceptable according to the AIAG norms. Moreover, the total gage R&R is higher than it is supposed to be according to the AIAG norms. This was also caused by low repeatability. The variance caused by repeatability corresponds to the variation in the measuring instrument. The measurement instrument for measuring the attenuation consists of roughly two parts. Firstly, the OTDR machine itself. An explanation of the OTDR could be found in Appendix D. The second part of the measuring instrument is the MAS system. This system's purpose is to connect the OTDR machine by making use of a 'measuring fibre' to the fibre that needs to be measured. More explanation about this procedure could be found in Section 2.3 and Appendix J.

A second experiment could be conducted to determine the cause for the high repeatability contribution. This is done by measuring one fibre multiple times connected to the OTDR directly without making use of the MAS. This experiment has been carried out and the attenuation values when making use of light pulses with a wavelength of 1550 nm were all about 0.186 dB/km. The attenuation values for the 1310nm wavelength are all about 0.331 dB/km. The results of an R&R gage study(crossed) on the attenuation values are given in Figure 4.3-3. This means that the connection and or position of fibre on the MAS has a big influence on the actual attenuation values, while the OTDR system itself is stably measuring the pulses consistently.

Gage R&R

Variance Components

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0,0000001	0,00
Repeatability	0,0000001	0,00
Part-To-Part	0,0104940	100,00
Total Variation	0,0104941	100,00

Process tolerance = 0,039

Gage Evaluation

Source	StdDev (SD)	Study Var (6 × SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	0,000305	0,001829	0,30	4,69
Repeatability	0,000305	0,001829	0,30	4,69
Part-To-Part	0,102440	0,614641	100,00	1576,00
Total Variation	0,102441	0,614644	100,00	1576,01

Number of Distinct Categories = 473

Figure 4.3-3. MSA test on the OTDR (n=47; data for 19-12-2022; source: TKF)

4.3.8 Results

A small summary of the metrics obtained from the MSA is given in Figure 4.3-3. The part-to-part variation is the biggest contributor to overall variation. The repeatability has no significant share in the total variation. When looking at the tolerances. The part-to-part variation is the biggest contributor. Although the repeatability also plays a slight role. The discrimination is good as well. The reproducibility is not mentioned in the table. This is the operator-to-operator variation and the variation induced by the operator-to-part interaction. But as only 1 operator is measuring it is not possible to deduce these metrics. The results compared before and after the wrongly measured fibres were taken out are depicted in Table 4.3-2

Table 4.3-2. comparing measuring system numbers before and after taking out wrongly measured fibres(n=54,72; data for 13-12-2022; source: TKF)

Fibres that get measured	Contribution	Tolerances	Study variation	Discrimination
All 12 fibres	79.58%	117.66%	89.21%	1
Leaving out wrongly measured fibres	28.73%	56.51%	53.60%	2

4.3.9 Validity and reliability assessment

Reliability indicates to what extent the results can be measured consistently when keeping all circumstances, the same. Repeatability is a good indicator of reliability as it gives the variation in the measuring instrument itself when keeping all conditions, the same. As the repeatability of the system is not good the reliability is also not in check. The internal validity of the attenuation measuring system is not that good, as the attenuation measurement system (human and instrument) is not working well to measure the attenuation values. For calculating the attenuation, the setup is good only the MAS is not able to make sure the measurements are consistent.

The cables mentioned above are all produced on sheathing line five. Moreover, cables often consist of similar tubes containing similar fibres. This makes it possible to generally implement the improvements also on the other cables. It makes it possible to also implement the solution or part thereof on the other cables. Also, control limits can be introduced on the fibres produced on other sheathing lines. First, the attenuation values for the fibres need to be compared and tested. This makes it possible to guarantee the external validity of the research.

4.4 Concluding remarks

To conclude, this section shortly answers the sub questions from Section 4.

'What is the development of the FTR percentage (of attenuation measurement at end control over time)?'

The first-time-right development showed some development. Although the employee interviews did not result in any potential causes being discovered. The FTR was also relatively low for the 288 cables having an FTR value of 93.3% as a moving average FTR, in comparison with the 94.6% average moving average of all cables. The full FTR development graph could be found in Section 4.2.

'What is the validity and the reliability of the attenuation measurement system at end control?'

The contribution towards variability that is attributed to the measuring system is 28.73 percent and the actual variability attributed to the difference in products (fibres) is 71.27 percent. So, the measurement system is a substantial contributor to the overall variability. The measuring system's variability is mainly down to the repeatability. As the repeatability of the system is not good the reliability is also not in check. The internal validity of the attenuation measuring system is not that good, as the attenuation measurement system (human and instrument) is not working well to measure the attenuation values

'What is the current process performance?'

The performance of the 288 fibre-containing cable are not according to a six sigma process, indicating that the ability of the process to being able to produce within the specification limits is low. However, if removing one cable containing outliers from the data set and taking the cables at which all 288 cables got measured, the performance indices were improved significantly, indicating that the process is running nearly within the six sigma requirements. However the performance of the 3rd measurement where not only 288-cables were taken into account gave low performance indices. When outliers were taken out the P_{pk} was 0.73 and the P_p 2.17.

5 Finding solutions

In Section 4 the current situation when it comes to attenuation variability got quantified, by making use of capability, performance indicators and FTR percentage of attenuation failures. Moreover, a measuring system analysis was carried out. It was concluded that the capability and performance values were not according to a six-sigma process. Additionally, the FTR for the 288 cables was 93.3 per cent at the moment of obtaining the data. As the target value is 98 per cent, it is far below the target.

In this section improvements for these issues will be found. In Section 5.1 improvements to the measurement system will be found. In Section 5.2 the relation between the influencing factors on the production line and the occurrence of failures will be derived. In Section 5.3 the control limits will be determined. Additionally, answers will be found for the following research questions.

'What are possible implementations to improve the mean and spread for the attenuation values at the end control?' (improve)

- *'How can the measurement system (human and system) be improved to realise a reduction in mean and spread for the attenuation at the end control?'*
- *'How can the statistical process control be implemented to improve the spread and mean of the attenuation values?'*
- *'What are the relations between FTR and influencing factors on a production level?'*
- *'What are good control limits for the attenuation measurement process?'*
- *'What production process steps are influencing the high spread and mean at end control the most?'*

5.1 Improvement of measurement system

5.1.1 Introduction

The causes for finding the improvements given in Section 5.1 have been derived from Section 4. Possible human improvement has not been needed since the variability caused by the different operators is only little. The improvements in measurement instruments have been derived from the MSA that has been used for deriving the variability components for the individual measurement system parts. Providing insights into what part of the system needs improvement. It was concluded that the variability is mostly caused by the difference in products(fibres), having a 71.27 per cent share in variability and the measurement system 28.74 per cent.

5.1.2 Human improvement

As indicated in sections 4.3.5, and 4.3.6 the variation contribution caused by the operators is only a very small component of the total variation. Also, the variation due to the various operators is only minimal in comparison to the variation caused by for instance replication and part-to-part variation. That is why the operator itself has not had that much influence on the measurement system itself. So, the added value to further implement any significant training that helps improve the operators' ability to operate the measurement equipment is not significant.

5.1.3 Measuring instrument improvement and implementation

When having a look at the MSA results and the OTDR graphs corresponding to the fibres being measured during the MSA, it was concluded that not all fibres were measured for attenuation over the whole length of the fibre. The system only measured the attenuation at the parts where the attenuation was decreasing stably.

The reason why the OTDR at the end control was sometimes not measuring the right piece of fibre length, was because the OTDR system used for doing the MSA was running the new software. This software had some differences from the old software used generally at the attenuation measurement places in the production plant. From now on, the system is always measuring the attenuation over the full length of the fibre no matter how the attenuation reduces over the full length of the fibre. This is a software adjustment that had been carried out by TKF's software supplier. This OTDR machine was first used after the measurements were done, only a few weeks before the MSA was carried out. So, this issue has not been influencing calculation variables like FTR percentage, capability, and performance indices significantly.

Improvements on the software/ Improving the failure handling process and documentation.

When doing the research, some difficulties came to light when analysing the failures. For instance, the explanation of the failures written down is not standardized. Operators have just the possibility to write a brief piece of text about the certain failure they occurred. It makes it difficult when someone writes about a certain failure and another operator writes something completely different about a similar type of failure. It is relatively hard to count the amount failures of a certain type that way.

Moreover, it is recommended to standardize the failure description more. Making only possible to select several standardized options to be able to find causes of issues easier in future. Describing a failure gets done differently for the various employees. Some employees write down 'fibre breaches' whereas only the attenuation is reduced significantly in one or multiple fibres. This could indicate a fibre breach, but this is not always the case. Moreover, also there was a description: 'white, yellow, and black tube few fibres with attenuation issues.' This is far too general, and it is hard to understand what part of the cable is involved exactly. CableMES provides partly a solution for the problem of not having standardized inputs for the failure description.

CableMES improvements

CableMES and the production process, in general, are described in Section 2.4. The introduction of CableMES has made the failure documentation part of the measuring step more straightforward. The operator scans the code belonging to a certain cable, subsequently, when there is a certain failure related to attenuation when measuring the reel, a certain quarantine procedure is automatically generated. This quarantine procedure cannot be overwritten by an operator.

The operators do not have a clear way of documenting the failures at end control, as described earlier. This makes it a bit hard to discover the failure causes. CableMES is providing improvements in this subject. As the failure gets automatically documented and linked to the certain fibre(s)/tube(s) having a failure. This offers partly solutions on the documentation of the failures occurring. Although it is important when providing a failure description, to give some recommendation about what, tube and fibre are involved. 'What is the OTDR device indicating on the certain fibre that is having a failure.' It is required to then use the following terms when wanting to indicate the attenuation graph behaviour, 'attenuation is too high', 'attenuation graph is not reducing stably', or 'the signal is lost completely'.

Improving the failure-handling process

Additionally, the cable gets rerolled onto another reel when a failure in attenuation is not solved by remeasuring. Once the problem is gone after rewinding no more investigation about the cause is carried out. Although it is very time-consuming, it is relevant to carry out an investigation every once in a while, before carrying out the reworking process. Being able to fix the problem by putting the cable on a new reel is not the ideal situation. It is better to not have the attenuation problem in the first place. That is why it is useful to investigate a certain cable indicating it has a failure regularly. Although the solution is probably rewinding. It makes sense to cut the piece of cable containing the failure out of the full cable. After that, it is important to find the failure spot and look at what point on the production line could have induced this failure.

Improvement on the MAS

After filtering out the fibres that were not measured correctly when conducting the first MSA, it was concluded that the main contributor to variation was the measuring instrument itself. The measuring instrument consists of the MAS and the OTDR system including the software. When doing another MSA where the MAS did not play a role and a certain fibre was measured in a stationary position, it was concluded that there was very little variation. So, the OTDR instrument itself is causing only very little variation in measurements. More investigation needs to take place about a possible upgrade of the MAS. It is not allowed to compare the standard deviation component due to repeatability with the standard deviation obtained from a very big sample size that has been used when calculating the capability and performance indices.

5.2 Relation between influencing factors on production level and FTR

To improve the production process, it is required to first derive the relation between the influencing factors on the production level given earlier and the occurrence of the failures concerning attenuation. For deriving those relations, a cause-and-effect matrix is used. Such a matrix is used to focus on the most important factors of influence. It is able to show the relationship between influencing factors and the results or effects of those influencing factors. The cause-and-effect matrix is derived by making use of expert opinion methodology (Theisens, 2016).

The expert opinion methodology provides an approach that involves collecting and analysing data from experts to gain insight and understanding of a certain topic. The information can be gathered through for instance surveys, interviews, and brainstorming sessions. This data can then be analysed, and conclusions can be drawn from the results. However expert opinion is one of the lowest forms of evidence in research (Hohmann, 2018). That is why the results from this brainstorming session should be used as guidance only.

5.2.1 Plan of approach

First, a brainstorming session is organized to come up with various attenuation problem causes. During this brainstorming session, first, a presentation about the research that was carried out until that point was done. This was mainly done to provide context for employees that were less involved with the research. After that, the various influencing factors were derived. These causes are the key process input variables (KPIVs) for a cause-and-effect matrix(Theisens, 2016). After that, the KPOVs (Key process output variables) for the cause-and-effect matrix could be found. The KPOVs are characterized by the results of certain influencing factors. These variables are given by the failures concerning attenuation that are occurring in TKF's case. So, these are consecutive; 'steps in the attenuation curve', 'attenuation is not as it should be', and 'fibre breach'. All KPOVs should be weighted by importance by customers or by the organization itself.

Thereafter, the employees had a couple of days to individually rate the correlation between the influencing factors (KPIVs) on the vertical axis and the different failures (KPOVs) on the horizontal axis. Additionally, the 3 different failures got rated. When multiplying the correlation values with the rating of importance and summing over all different failures it is possible to come up with a total weighted average score for every influencing factor per individual.

A filled example of such a cause-and-effect matrix for an individual employee could be found in Appendix M. This assignment brought insight into the correlation of the different influencing factors with the failures. The rating of importance is a rating from (1-10) and with 10 being very important to improve and 1 is not so important to improve. The correlation coefficient goes from 0 to 9 and includes the values: 0(KPIV does not affect KPOV), 1 (KPIV has a weak effect on KPOV), 3 (KPIV has a moderate effect on the KPOV), 9 (KPIV has a strong effect on KPOV).

In the second meeting, the results got discussed and combined. A combined score can be calculated when taking the mean of all individual scores. During this meeting also influencing factors and information that was not clear to everyone was explained. Similarly, an occurrence score was determined for the different influencing factors. The occurrence score is a score from (1-10) with 1 (being a cause that is not occurring normally), 3(means it is sometimes occurring) and 10 (means it is occurring often). The occurrence scores were derived with consensus during the meeting and were not derived individually. The occurrence score is based on the rate of occurrence of the various causes. Moreover, slight alterations in the causes were done. Also, the individual scores were adjusted slightly in case there was something not totally clear.

After that is done, the highest-scoring KPIVs/causes could be found. These causes on the basis of expert opinion are the causes that should get addressed the earliest when wanting to reduce the failures represented by the KPOVs. The 10 highest scoring KPIVs are given in Table 5.2-1. The KPIVs are grouped by an element of the 6m's. During the first brainstorming session, a fishbone diagram was used to identify all causes and to make sure that only the primary causes are given (Liliana, 2016). The causes are categorised using the 6m method. So, the highest influencing factors for the FTR or the attenuation failures occurring could be viewed in Table 5.2-1. More explanation about the KPIVs and ways to reduce the KPIVs will be given in Section 5.5. The causes will be categorised in the 6m method. The 6m's represent consecutively materials, methods, man, machines, mother nature, and measurement. These various cause categories are used to categorise the possible causes (Liliana, 2016) For every possible cause and failure, the weighted average score is calculated.

Table 5.2-1. Highest-scoring KPIV's

main group	KPIV	combined score	occurrence score	combined*occurrence score
machines	Tubes in a cable are longer than they are supposed to be	163	10	1630
machines	Tubes do have not enough length for the cable	160	10	1597
materials	The reel core diameter is too small	160	10	1597
man	Lining out the tubes correctly	100	10	997
materials	Tube sticks to the outer sheath	64	10	643
materials	Tape is not able to completely enclose tubes	54	10	543
materials	Lumps and necks high spec limit	81	3	244
materials	The tube outside contains imperfections	74	3	223
measurement	Not good accuracy MAS	68	3	204
materials	The tube inside contains imperfections	56	3	169

The overlength or under-length of tubes in the cable are significant influencing factors. Although during the brainstorming session, it was not exactly determined what the probability and rate of occurrence for the certain influencing factor were. That is why these influencing factors could not be classed as highest scoring and further research needs to be done to determine to what extent the exact problems occur. However, for the moment the occurrence score for both influencing factors has been classed as a ten.

5.3 Determining control limits.

5.3.1 Preparing data for calculating control limits.

When determining the control limits, it is important to filter the attenuation data. This is down to the fact that a lot of attenuation measurements take place. The data from all OTDR equipment at the quality control stations in the fibre optics cable plant get stored in a database. This data can be downloaded in an Excel file and can be filtered. Table 5.3-1 provides the criteria at which the data must apply for calculating the control limits.

Table 5.3-1. Filter criteria for calculating control limits.

Filter criteria	Values to include	Explanation
Measuring mode	MAS	The 288 cables are only measured at the end control
Description	STC	The soft tube cable will be looked at
Measuring number	3	MAS is only able to measure 120 at once, so 3rd measurement is the first possibility that 288 cables are fully measured. Only the 'virgin' measurement is taken when calculating the control limits. Higher measuring numbers correspond to reworked or improved products.
Number of fibres	288	Some measurements are stopped while not having measured all fibres.
Description 2	288x SM G.657.A2 (24x12)	A cable containing 288 optical fibres and tube configuration (24 tubes containing 12 fibres).
Sort time stamp	Timestamp: ascending	When making a control chart it is important to look at the data from old to new.
Wavelength	1550nm	The attenuation data obtained from the measuring equipment measuring on a 1550 nanometre wavelength is taken.[2]
Containing failures	Cables containing no failures concerning attenuation.	For the right control limits, it is required to obtain data that contains no failures.
	Include only values other than 0	When having an attenuation value of near or on 0, the product itself is not having issues, only the system might have issues as there should be a certain amount of optical loss through the cable and this can not be 0 dB/km. (Indicating a system failure.)
Timespan	From 12-05-22/13-01-23	As there should be a lot of data points to calculate the control limits and the data is only being captured in its current form from 12-05-22, it is easiest to take this period.

[2] Measuring at 1550nm results in making visible failures that do not occur when only measuring at 1310nm. Although failures being visible at 1310 nm are always visible at the OTDR graph when measuring at 1550nm.

Some statistics from the filtered and adjusted data are given in Table 5.3-2. The data is skewed to the right. Also, the kurtosis of 34.74 is indicating that the distribution of the data is relatively peaky and non-normal. The kurtosis should be close to 3 for the data to be normal. The skewness should be between -2 and +2 for the data to be normally distributed. The kurtosis should be between -7 and 7 to prove the data is normally distributed. The skewness indicates it is normally distributed because the skewness of -1.89 is between -2 and 2. The kurtosis does not indicate the data is normally distributed as the kurtosis of 18.0 is not between -7 and 7.

Table 5.3-2. statistical data (n=49536; 12-05-22/11-01-23; source: TKF)

Statistics

Variable	Total Count	Mean	SE Mean	StDev	Variance	Minimum	Q1	Median
attenuation	49536	0,18953	0,000011	0,00252	0,000006	0,16000	0,19000	0,19000

Variable	Q3	Maximum	Range	IQR	Skewness	Kurtosis
attenuation	0,19000	0,22000	0,06000	0,000000	-1,89	18,00

5.3.2 Deriving control charts with control limits.

In the literature review phase in section 3.2.2., an extensive breakdown of possible control charts to be used is given. Additionally, information is provided about how the control charts and their control limits are constructed. The Xbar-S chart will be used. When filtering the attenuation data as given in 6.3.1. can derive control charts with their corresponding control limits. The Xbar-S charts are derived from the attenuation values when using the filter criteria given in Table 5.3-1. The control charts, given in Figure 5.3-1 and Figure 5.3-2 are not providing the exact values for the upper and lower control limits. Those values could be obtained in Table 5.3-3.

The lower control limits have been removed, as having a low number in attenuation indicates that the corresponding cable has only a little amount of light reduction. That is why it is not necessarily needed to include the lower control limits as well. All blue points represent the subgroup mean and subgroup standard deviation values. It is concluded that a large number of points is situated below the lower control limits in both the Xbar and the S-chart. As the mean attenuation and the standard deviation of the attenuation values should be as low as possible it is not needed to take those points into consideration.

Table 5.3-3. Upper and lower control limits for sample standard deviation and mean (n=49536; T=12-05-22/11-01-23, Source: TKF)

	Upper control limit	Lower control limit
For sample mean	0.18983 (dB/km)	0.18923 (dB/km
For sample standard deviation	0.001925	0.001497

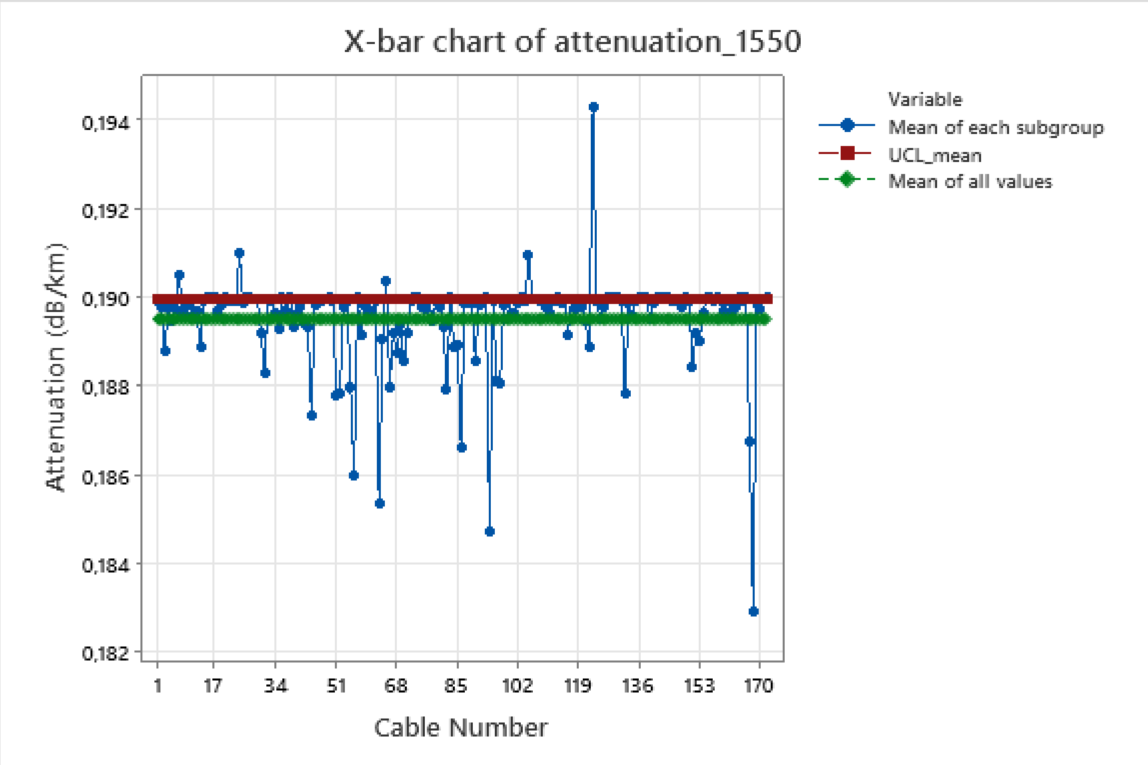

Figure 5.3-1. X-bar chart of attenuation from filtered data (0 values and failures not included) (n=49536 (172 subgroups); 12-05-22/11-01-23; source: TKF)

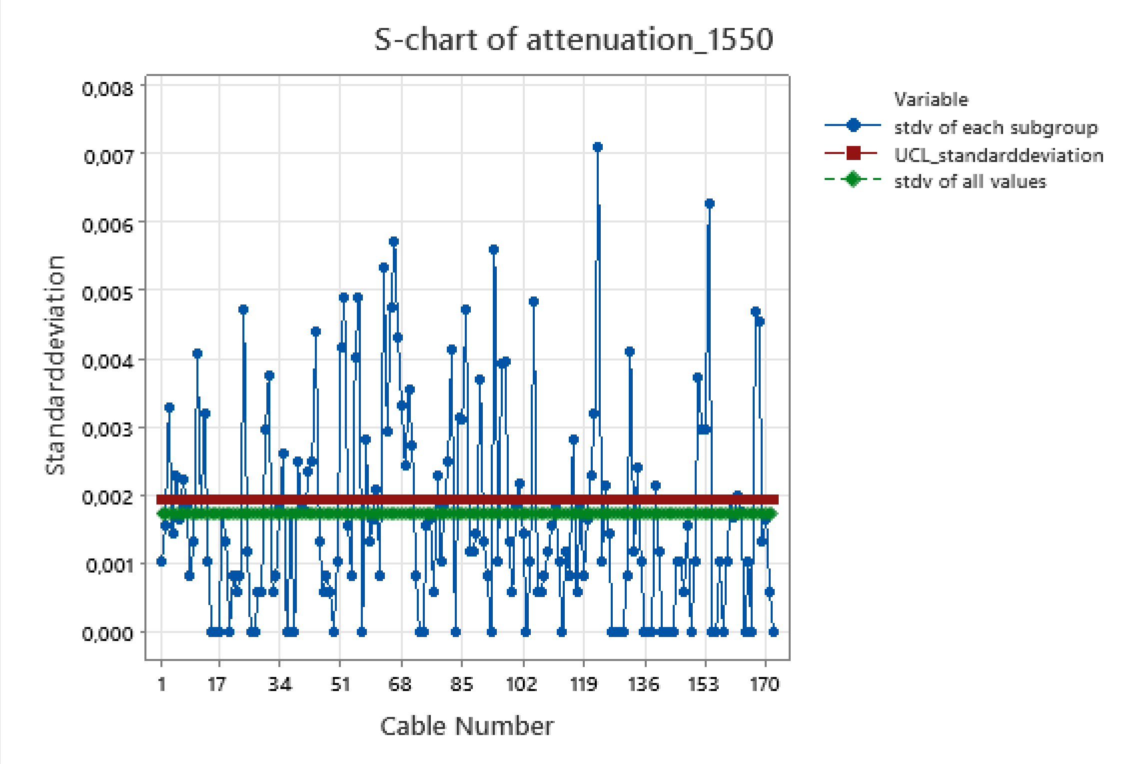

Figure 5.3-2. S-chart of attenuation from filtered data (0 values and failures removed) (n=49536 (172 subgroups); 12-05-22/11-01-23; source: TKF)

Figure 5.3-1 is plotting the sample means of the 288 cables. When studying the X-Bar it is concluded that there are a lot of out-of-control situations. This is a situation in which either the sample mean or sample standard deviation is higher than the upper control limit for the mean or standard deviation respectively. The amount of values above the UCL limits is relatively little. Figure 5.3-2 represents the S-chart of attenuation. During the full period, there were quite some out-of-control situations whereas the X-bar chart provided less out of control situationsCurrently, the specification limits are at 0.224 dB/km. And there is no specification of the standard deviation for the cable.

When implementing these control limits would result in initiating reasons for conducting more research to optimise the process. Additionally, making sure that when the process drifts away from the mean, action will be undertaken. A restriction of setting up control limits is that when the process is started running out of control then measures can be taken on time. So, the cables being produced must get measured as soon as possible. This is needed to be able to intervene in the process on time before products are having faults caused by the same problems on production level.

5.4 Rewinding

When going through the data it is recognized that the rewinding process often occurs as a way to repair the cable, when attenuation issues exist. The 3 failures occurring could be most of the time solved by rewinding the cable. When looking at sheathing line 5 About 65 per cent of the time the 3 failures get resolved by rewinding the cable that has one of the 3 given failures. For instance, when the OTDR graph gives the suspicion that there is a fibre breach. Mostly the OTDR graph then shows a sudden reduction in attenuation. This could be the case when a certain tube contained in the cable has a certain entrapment.

Subsequently, most of the light is not able to pass through at that point. After the rewinding process, the indication of a fibre breach might disappear on the OTDR graph when testing the attenuation again. Due to the force exerted on the cable, the tubes contained in the cable get stretched slightly and obtain relaxation making sure the cable content is coming back to the position as supposed to be, without any entrapments.

Since such a large proportion of the failures are resolved by doing the rewinding process, it is important to find out why is the rewinding process needed in the first place, and how can maybe a part of the rewinding process get incorporated into the actual sheathing process to make sure the failures occurring could be minimised and the rewinding process is not needed anymore when wanting to solve one of the 3 failures given earlier.

5.5 Possible improvements on production level counteracting the failures.

Problem-solving method.

The influencing factors for the three failures occurring are gathered during a brainstorming session mentioned in Section 5.2. After that, a cause-and-effect matrix is made to determine the highest-scoring influencing factors or KPIVs. Section 5.2 depicts this. The highest-scoring causes are given in Table 5.2-1. In this section, possible improvements for the highest-scoring causes are given.

The reel core diameter is an important cause of failures. Especially when having a cable with a high diameter, the cable can only bend a certain amount before it gets damaged internally, and attenuation problems occur. When a customer orders a short piece of a high-diameter cable, the cable will be wound up a reel that has a relatively small core diameter, when comparing it with the core diameter from the reel that is normally used when transporting a higher length of the high-diameter cable. This is mostly due to transportation costs. It is costly to transport a big reel carrying a cable having only a short length.

Such a cable has often attenuation problems. After the failure is detected, normally the reel gets wound up onto a bigger reel. When attenuation is in check, the reel gets rolled back onto a small reel and gets sent to the customer. This process could be simplified by rolling the cable directly onto a high core diameter reel, after which it is required to measure the reel. After that, it is vital to put the cable back onto a small core-diameter reel.

According to the employees that participated in the brainstorming session. Tubes could get tangled with each other when bundled together to form a cable. This may result in friction and damage to the tubes and fibres. The problem's probability of occurrence as well as its influence on the FTR is relatively high. Counteracting this problem could be done by taking good care in the preparation steps when the sheathing line switches over from one cable to the other. Especially it is important to guide the tube well through the various guiding holes and along the guiding wheels.

When the tape does not enclose all tubes correctly the probability of the tubes melting together or getting stuck to the outer sheathing is present. This results in the fibres obtaining damage. This damage could result in attenuation issues. The incorrect application of tape could result in entrapment in the cable. Causing possible attenuation issues as well. Special care could be taken to apply the tape and to make sure the tape application is maintained during the production of the full cable length.

Certain production issues concerning the tube are lumps and necks. Lumps and necks are narrower and wider parts of the tube. The outside of the tube could also have an imperfection, caused by the coating process. The extrusion element might have had some pollution. Resulting in an imperfect coating layer. The issues do not occur that often, resulting in a low occurrence score. It is of less importance to focus on addressing these issues.

The interpretation of the attenuation issues on the OTDR graph is an important step when assessing the failures. Being able to recognize certain patterns in the graph is very important, for assessing what failure occurred. When assessing the patterns on the OTDR graph it is difficult to exactly point out what it represents. Currently, an operator can determine that a pattern on the OTDR graph is caused by a fibre breach, whereas this should not necessarily be the case. The fibre breach category can be changed to attenuation curve drops completely. This holds open the possibility of resolving this issue, for instance after rewinding.

5.6 Concluding remarks

'How can the measurement system (human and system) be improved to realise a reduction in mean and spread for the attenuation at the end control?'

After conducting the MSA it has been concluded that the MAS is responsible for about 28 per cent of attenuation variability, whereas the difference in products account for about 72 per cent. So an improvement on the measuring system could be there for significant.

'How can the statistical process control be implemented to improve the spread and mean of the attenuation values?'

'What are good control limits for the attenuation measurement process?'

SPC has to be implemented by making use of control limits. These limits have an upper attenuation limit for a mean of 0.18994 dB/km and an upper standard deviation limit of 0.001925 for each sample. 36 of the 172 cables are above the UCL for both the standard deviation and the mean attenuation value. That is why interventions do occur relatively often. These control limits enable the operators' clear indicators when intervening and finding causes need to take place. The control limits need to be applied on the data of the third measurement, containing 288 fibres.

'What are the relations between FTR and influencing factors on a production level?'

'What production process steps are influencing the high spread and mean at end control the most?'

The relations according to the expert opinion study and the resulting cause and effect matrix could be found in Table 5.2-1. Most influencing factors on production level according to the expert opinion study done are:

- The reel core diameter being too small.
    - The process of putting a large diameter short length cable onto a small core diameter reel often provides attenuation issues when measuring. When the cable is on a larger core diameter reel, the problem often gets taken away. It was concluded that this process step is simplified by immediately putting the cable onto a bigger reel and measuring it, before putting it onto a smaller reel and sending it out to the customer.

- Lining out the tubes.
    - Additionally lining out the tubes correctly was an important part of mitigating attenuation problems. It is especially important to take good care of the preparation steps when switching from one cable to the other.
- Tube sticks to outer sheathing/ Tape is not able to completely enclose tubes
    - When the tube sticks to the outer sheathing it will result in the possible damage of fibres contained in the tube.
    - The application of tape around the tubes counteracts this issue.
- Lumps and necks have a high spec limit on the sheathing line
- Tube outside/inside contains imperfections
    - Resulting in possible damages to the fibres, causing attenuation issues.

6 Attaining improvements in future

In Section 5 possible solutions were derived, to improve the mean and spread of the process. In this section, a plan to implement the solutions provided in the previous section is given. During this phase, an implementation of the new way of measuring as well as an implementation recommendation for training will be given. The new capability and performance indices are given. Moreover, the KPIs and ways needed to monitor the process are given.

In Section 6.1.1 improvements to the software user interface of the measuring system are given. As it is required to include the Xbar-S chart in the attenuation measurement program, it is required to alter the attenuation measurement software. In Section 6.1.2 recommendations will be provided to implement training for the measurement procedure as well as the failure managing procedure. This is required as the implementation of SPC provides the need to include training for the workforce controlling the measurements. In Section 6.2 new performance indicators are provided. These new performance indicators provide information about the new performance of the system. In 6.3 and 6.4 key performance indicators (KPIs) as well as ways to monitor the process spread and mean are provided. To be concise answers will be found for the following questions.

'How to make sure the new way of measuring and analysing the measurements will be maintained over the long term? (control)'

- *'How to implement training for the operators using the new way of analysing the testing data?'*
- *'What are the process capability and performance indices after improvements are implemented?'*
- *'What KPIs are needed to measure the current process performance concerning attenuation?'*
- *'How to monitor the performance of the proposed changes on the production level to improve spread and mean?'*

6.1 Implementing training for the new way of measurement and software

6.1.1 Software UI(user interface) for doing the measurements.

When applying SPC, it is required to introduce new testing software. As the task is implementing SPC for the 288-fibre cable at end control, it is useful to provide software requirements for implementing SPC at end control. SPC is already implemented on the colouring line, so the software for measuring the fibres will be adjusted to be applied for running at the end control. The adjustments that were recommended will be partly carried over to the SPC monitoring software at end control or can be slightly adjusted (Ruiter, 2022). Changes need to be done in a few aspects. First of all, the backend needs changes, as at the end control the fibres get measured in samples, in comparison with measuring the individuals at the colouring line.

Backend

The attenuation will get measured in samples by making use of an Xbar-S chart. The control limits will be calculated by making use of the last 25 cables. Additionally, the attenuation increases concerning an unmodified fibre should also be used in the UI and backend. Every cable should be separately monitored, and control limits should be calculated accordingly.

User interface

The attenuation increase should be used in the user interface. This is the increase in attenuation with respect to the unmodified fibre. ‘Lijn nr’ (in the header as well as on the right-hand side of the print screen) should be changed to ‘mantel lijn nr’ (sheathing line nr). Corresponding to the last process step that is done before end control. The ‘vezeltype’ (fibre type) on the top and the right corner is not needed anymore to use at end control. As the SPC is done on the cable level, ‘vezeltype’ (fibre type) should be changed to ‘kabel type’ (cable type).

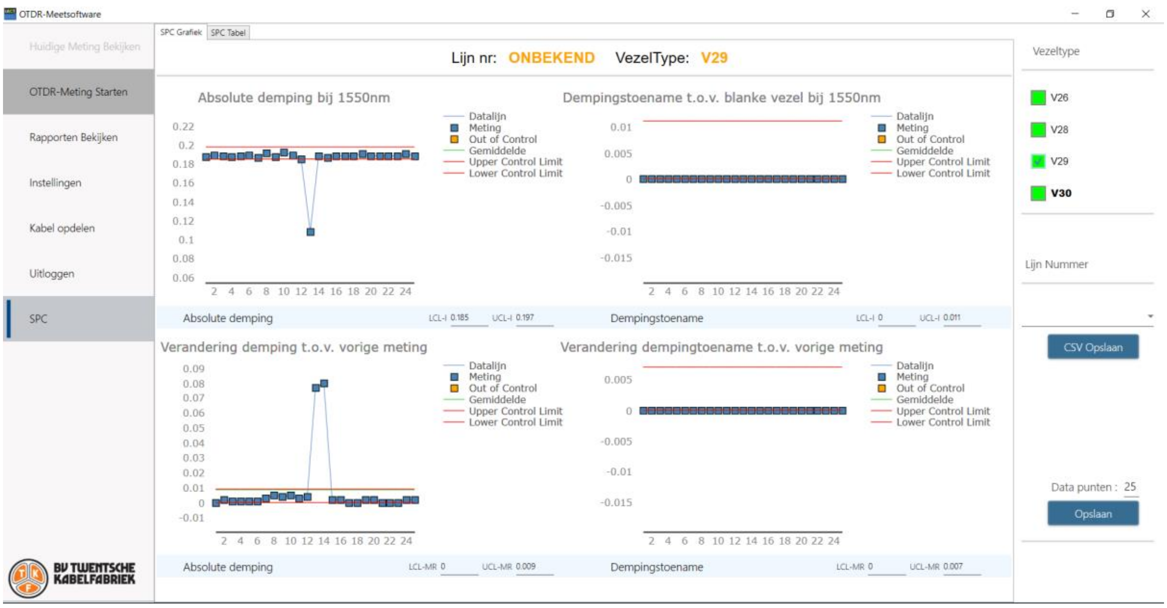

Figure 6.1-1. OTDR measurement user interface

Data visualisation

Next to the Xbar-S chart that will be used instead of the I-MR chart in the software, it is also required to be able to gather data from the attenuation values. The right part of the UI (user interface) should be changed to be able to gather the attenuation data from a certain specific fibre being contained in a certain specific tube and cable, made on a specific production line. Also, it should be possible to leave certain fields of the previously mentioned criteria open, to be able to gather the data from for instance the entire sheathing line 5, 288-cable, or orange tube. This software will be mainly used by the operators, but also managers are able to use this software.

6.1.2 Implementing training recommendations.

Moreover, it is a good idea to let the operators being responsible for measuring at end control get the opportunity to get familiar with the new control charts that are used. So first it is important to explain why it is important to introduce control charts at end control. Moreover, it is required to explain the Xbar-S chart as well. Additionally, it is required to provide steps needed to undertake when an out-of-control situation occurs. Providing steps needed to undertake when it comes to the highest scoring influencing factors. So, if an attenuation problem occurs there should be an out-of-control action plan in place for providing guidance about what to do. This is based on the top 5 highest-scoring influencing factors. It is not needed to train the operators for the general way of taking measurements with the MAS and the OTDR, as the variation due to the operators is only a very little share of the total variability in the total attenuation variability.

6.2 New performance indices and short-term capability

After implementing the control limits that are given in Section 5.3, the new capability and performance measures that can be reached can be obtained. Before calculating the capability and performance indices, a run chart should be made with the filtered data given in Section 5.3. This chart is made to test if the process has no special non-random patterns. The run chart of the filtered data from Section 5.3 is given in Figure 6.2-1.

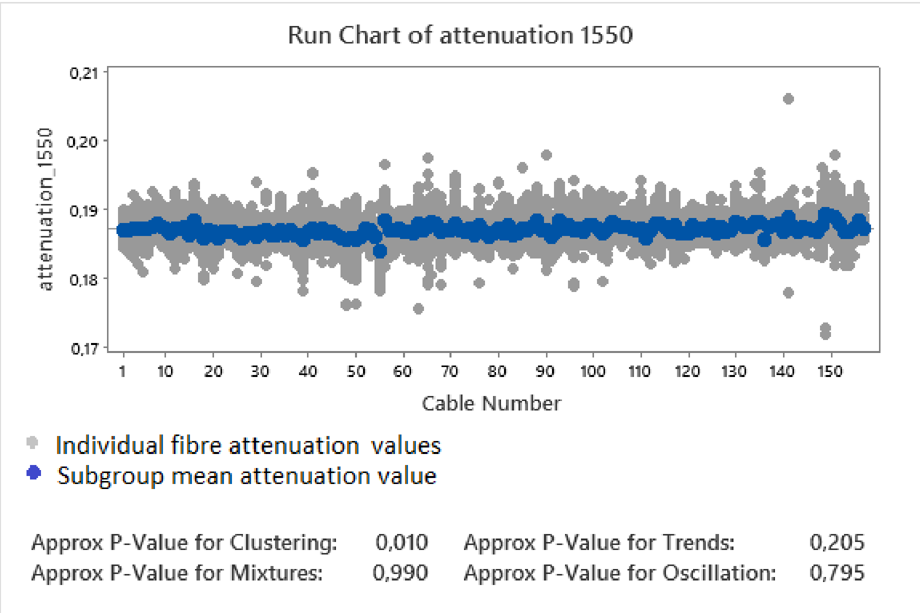

Figure 6.2-1. run chart of attenuation 1550nm (n=45216; 11-05-22/01-11-22; source: TKF)

All P-values are above 0.05, so it is not possible to reject the null hypothesis: Indicating that there is no special cause variation in the data (Theisens, 2016). In Appendix L a plot of the attenuation capability and performance for the filtered data and unfiltered data is given. The period is equal to the period of the data given in 4.1. This is done for a straightforward comparison.

The performance indices are calculated by making use of the data provided in section 4.1. The data is filtered and all mean attenuation values for the different subgroups are filtered. Simulating the application of the control limits calculated earlier. After that the performance indices get recalculated. After that the performance indices get compared with the performance indices calculated over the same data with taking into consideration the control limits. So, all cables having a subgroup mean or a subgroup standard deviation above the UCL for the standard deviation or mean will be filtered out when calculating the performance for the new situation.

Table 6.2-1. performance and capability indices with or without control limits applied.

Control limits applied	**Wavelength(nm)**	$\boldsymbol{P_p}$	$\boldsymbol{P_{pk}}$
Yes	1550	27.55	9.06
No	1550	2.17	0.73

Table 6.2-1 represents the performance indices for the filtered and unfiltered data. Simulating the fact that the process is running below its upper control limit. The $\boldsymbol{P_p}$ and $\boldsymbol{P_{pk}}$ performance indicators are both higher than 1.5 meaning that only 3.4 ppm are outside of the specification width of 12 standard deviations of the process.

When calculating the short-term capability of the process an average period is taken, containing 23 cables. This sample size did not contain any failures with respect to attenuation. The period is from 17-07-2022 till 29-07-2022. This has provided a C_p of 24.83 and a C_{pk} of 8.28. Both of these values are well within the six sigma requirements of being over 2. A process capability report for the short-term capability is provided in Appendix L. Meaning that the capability of the process to run within its specification limits is very good. This gives the indication that the specification limits for the capability on the short term are too wide and could be narrowed. Additionally, the ability of the process to run close to its mean is not that good, meaning that the process is not that good centered within its specification limits. This is indicated by the P_{pk} providing a significantly lower value than the P_p.

6.3 KPI's needed to control the performance of the process.

Maintaining the recommended improvements is an important part of the solution. That is why key performance indicators need to be determined to make the process performance monitoring is as straightforward as possible. KPIs correspond to a set of measures that are most important for the current and future success of the company(Parmenter, 2007).

The most important KPIs needed when controlling the process are the capability and performance indices given in Table 6.3-1. Further explanation about these variables could be found in 1.3. Both parameters are needed for indicating the process variability and the ability to run within the control or specification limits as well as the ability to run close to the mean of the process. So, both spread and deviation from the mean are represented by the performance and capability indices. The performance indices should be used for monitoring the process spread and deviation from mean for the long term and the capability indices for the short term. Furthermore, the FTR is a good indicator of the spread and general performance of the process. The FTR indicates the share of the product having no attenuation-related failures. Further explanation about FTR can be found in Section 1.3.

Table 6.3-1. optimal values for performance and shot term capability indices for 288 cables.

KPI	Goal values	Values based on filtered data
C_p	>2	24.83
C_{pk}	>2	8.28
P_p	>1.5	27.55
P_{pk}	>1.5	9.06

Table 6.3-2. Current FTR value for 288 Cable

KPI	Goal values	Current value
FTR	98%	93.3%

6.4 Ways to monitor the spread and mean of the process.

Testing improvements on production and measuring process.

It is required to test the improvements on the production level as well as the applied control limits. The improvements on the production level as well as the improvements in the measuring system could be monitored with the FTR. It is a good idea to keep calculating the FTR every month monitoring if the FTR has decreased or not. Moreover, the production and measurement system improvements can be measured by the capability and performance indicators. The ability of the process to run within the specification limits can be measured by the capability and performance indices.

Applied control limits.

A good indicator for measuring the performance of the control limits is the percentage of out-of-control situations. Having a high number of out-of-control situations could indicate that the control limits were set too tight. It could also indicate that the process is having too much variability and a certain part of the production or measuring process is not performing as it should be. As the control limits are calculated from the last 25 cables, the control limits could get wider or narrower over time, making sure the control limits are not rigid and move with the process.

6.5 Concluding remarks

'How to implement training for the operators using the new way of analysing the testing data?'

- Provide training for the operators with respect to the Xbar-s chart and the new software enabling the operators to use statistical process control at end control.
- Provide training with respect to the out-of-control situations existing, enabling the operator information and steps to undertake when an out-of-control situation takes place.

'What are the process capability and performance indices after improvements are implemented?'

- When control limits are applied the performance indices have values of 27.55 for the P_p and 9.06 for the P_{pk}. Using short term data the capability have values of 24.83 for the C_p and 8.28 for the C_{pk}. Those values are well within the six sigma specifications.

'What KPIs are needed to measure the current process performance concerning attenuation?'

- Both the capability and performance indices as well as the FTR percentage are good indicators for monitoring the spread and mean of the process. With capability indices should be calculated with short term data and performance over the long-term data.

'How to monitor the performance of the proposed changes on the production level to improve spread and mean?'

- The improvements on the production level as well as the improvements in the measuring system could be monitored with the FTR. Keep calculating the FTR every month looking at if the FTR has decreased or not.
- Moreover, the production and measurement system improvements can be measured by the capability and performance indicators.
- The control limits should be calculated from the last 25 cables, taking the third measurement containing 288 fibres.

7 Conclusion

7.1 Overall conclusion

During this research, it was needed to find a way to implement SPC at the end control as well as find improvements improving the FTR of the failures given, specifically for the 288-cable. The conclusion is divided in points with sub bullets providing extra information on the main points.

- The 288-Cable has been chosen to do the research on.
    - 39.33 per cent production volume of sheathing line 5.
    - Has an above average FTR value.
- Measurement system contains variability.
    - The varaibililty contributor of the measurement system was 28.73 per cent whereas the variability of the difference in part attributed to 71.27 per cent.
    - The main contributor to the variability was repeatability. This corresponds to the system's inability to measure the same values when all circumstances are the same. It was determined that the MAS was the main contributor to the variation.
    - It was also concluded that since the MAS was not working as it was supposed to be working, the internal validity is not in check.
    - The measurement system was not always measuring attenuation over the full length of the fibre, this has been resolved with a software update.
- The Xbar-S chart is the main chart that is needed for the data that is being analysed.
- Rewinding is the main solution for attenuation related issues.
    - 65 per cent of the attenuation related failures got resolved with rewinding a failure containing cable on to another reel.
- Control limits have been determined
    - As having the process running below its control limits has not a negative influence on the process, only the upper control limits get considered.
    - The control limits have been calculated on data not containing attenuation issues.
    - The data had to be filtered, because the attenuation measurement process is structured in such a way that it is not possible to just take any measurement that is measured in the calculation of control limits. This is mainly down to having control limits on the sample and not on the individual values.
    - The UCL’s for the subgroup mean is 0.18983 dB/km and for the subgroup standard deviation 0.001925.
- Performance indices got calculated before and after the simulated application of control limits on long term data.
    - The performance indices for the current process were subsequently 2.17 for the P_p and 0.73 for the P_{pk}. Representing a process not running within six sigma specifications.
    - The performance indices after the simulated application of control limits were all above 1.5, well within six sigma specifications.
- Capability indices got calculated on short term data.
    - The capability indices were 24.83 for the C_p **and** 8.28 for the C_{pk} well above the six sigma boundary of 1.5.

- The specification limits could be adjusted as the short term capability is very high and the process is not centred that well withing the specification limits.

- Capability and performance indicators are good KPI's for monitoring the variability of the process.

7.2 Recommendations

After having conducted the research at TKF some recommendations could be made.

- Doing research on the failed cables before rework
  - First, to help find the root cause of how the attenuation failures occurred, it is required to not immediately rewind all cables onto a new reel, but first investigate how the failure could have been caused. Not needing to rewind the cable in the first place is more beneficial than a standard rewinding of the cable.
  - Additionally, there is the possibility to find a solution for trying to incorporate the rewinding process into the sheathing line, avoiding the necessity to rewind when a failure occurs.
- Alter the testing software at end control
  - Enabling the use of Xbar-S charts.
  - Change the attenuation failure descriptions to: , 'attenuation is too high', 'attenuation graph is not reducing stably', or 'the signal is lost completely'.
- Implementation of SPC requires little stock in between sheathing line and end control.
  - When applying SPC it is required to have a high throughput at the end control. Possible interventions on the sheathing line are done in time before another product is produced on the same line. If there is a pile-up of cables between the sheathing process and the end control, it might result in the disapproval of multiple cables that have been produced.
- Finding control limits for the other cables
  - Finding control limits for the attenuation for the other cables produced on other sheathing lines is useful. Making sure to have SPC for attenuation measurement at the sheathing line fully covered.
- Provide training for attenuation measurement staff at end control.
  - To assure the operators can work with SPC at end control, it is needed to provide training about the analysing of measurements and conducting measurements but also on the failure handling process.
- Doing research about alternatives for the MAS
  - When considering the measurement system, the MAS is providing a significant amount of variability. To make sure the variability in the measurement process step is minimized, it is recommended to research an alternative system replacing the MAS.
- Doing research about influencing factors
  - Moreover, for further research, it is important to go into more detail on the influencing factors. The overlength and under length and their influence on the failures given are not determined exactly.

7.3 Discussions

As explained earlier there are quite some limitations and discussion points to the research done. For instance, only the 288-cable gets considered when determining the control limits and determining the capability and performance. At sheathing line 5 only, there are 32 distinct variations of cables produced. As mentioned earlier, it would not be possible to include all control limits for the various cables. That is why the most produced cable having a relatively low FTR has been looked at. Ideally, control limits for all cables should be determined.

There is some discussion point about the results of the MSA that was done for testing if the MAS or the OTDR was the contributor to the large variability in the measurement system. It could be argued that this test decreases the repeatability share in variability. This is the case because during this test the attenuation at a wavelength of 1550nm and 1310nm gets measured, resulting in a lot of part-to-part variation and less variation due to repeatability, whereas the MSA done earlier was done on seven more similar fibres all measured on 1550 nm resulting in a lower part-to-part variation component.

When filtering the values for attenuation issues, simulating the fact that the process is running within control limits the performance indices can be calculated accordingly. This way of testing the control limits can be criticised as it assumes that the measured values after having implemented the control limits are running within the specification limits. This is assumed because the control limits will give triggers for the operators to act and check influencing factors before the attenuation exceeds specification limits.

During the summer break in weeks 31 and 32 of 2022, the production was shut down. This could have influenced the number of out-of-control situations right thereafter. Setting up a production process could take some time before the production process is running stably. Although the FTR of the attenuation-related failures did not change significantly.

During the MSA, only the measured results were taken for the data where the software was measuring the fibres over the full length. So, this has not significantly influenced the results from the MSA. Also calculating the FTR has not been significantly influenced by the system not being able to measure the fibres over the full length. Only a small number of weeks before the MSA took place included the wrongly measured fibres. The calculation of the performance indices has also not been influenced significantly, because the data derived from measuring during this period was only very little in comparison to the full dataset.

Too, only the upper control limits will be considered as having a low attenuation value is not a bad thing as attenuation should be as low as possible. Possible faults in the measuring equipment could be kept unnoticed when only using UCLs. It is relatively hard to determine the capability and performance indices when control limits are applied. The decision is made to use the data when having removed the measuring failures and normal failures when calculating the capability and performance indices for the new situation.

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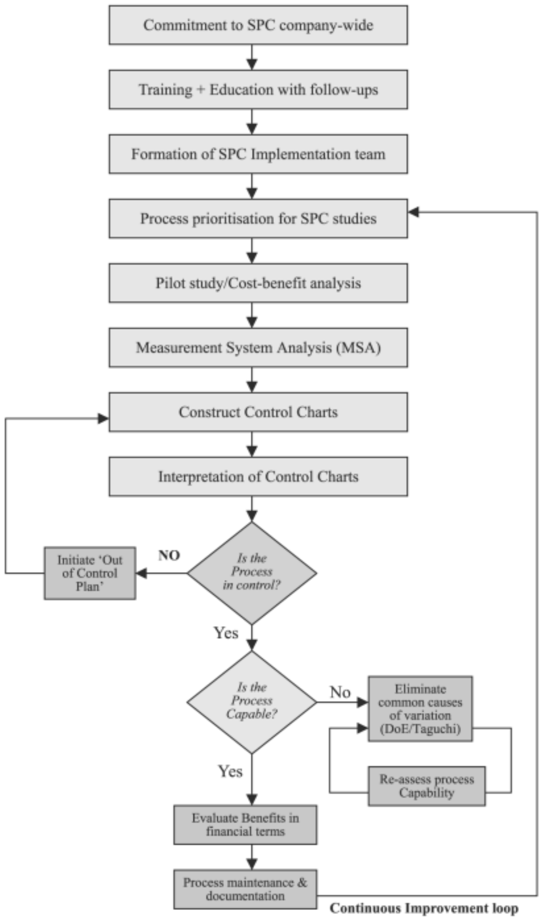
9 Appendix

A. Produced STC cables with mentioned failure type (FTR not corrected)

Table APX 9-1. Produced STC cables with attenuation failures

MIK	STC			
Type of cable produced	# cables produced	number of failures	FTR (not corrected)	share of total production
12x SM G.652.D (1x12)	50	20	60,00%	4,43%
12x SM G.657.A2 (1x12)	51	0	100,00%	4,52%
12x SM G.657.A2 (2x6)	74	2	97,30%	6,55%
144x SM G.652.D (12x12)	22	6	72,73%	1,95%
144x SM G.657.A1 (12x12)	8	0	100,00%	0,71%
144x SM G.657.A2 (12x12)	86	4	95,35%	7,62%
24x SM G.657.A2 (2x12)	22	0	100,00%	1,95%
24x SM G.657.A2 (4x6)	33	0	100,00%	2,92%
288x SM G.657.A2 (24x12)	444	50	88,74%	39,33%
36x SM G.652.D (3x12)	2	0	100,00%	0,18%
36x SM G.657.A2 (3x12)	23	0	100,00%	2,04%
432x SM G.657.A2 (36x12)	45	2	95,56%	3,99%
48x SM G.652.D (4x12)	4	0	100,00%	0,35%
48x SM G.657.A2 (4x12)	21	0	100,00%	1,86%
48x SM G.657.A2 (8x6)	56	0	100,00%	4,96%
576x SM G.657.A2 (48x12)	24	2	91,67%	2,13%
6x SM G.657.A2 (1x6)	3	0	100,00%	0,27%
720x SM G.657.A2 (60x12)	34	2	94,12%	3,01%
72x SM G.652.D (12x6)	3	0	100,00%	0,27%
72x SM G.652.D (6x12)	8	3	62,50%	0,71%
72x SM G.657.A2 (12x6)	11	2	81,82%	0,97%
72x SM G.657.A2 (6x12)	25	4	84,00%	2,21%
96x SM G.657.A1 (8x12)	13	0	100,00%	1,15%
96x SM G.657.A2 (16x6)	5	2	60,00%	0,44%
96x SM G.657.A2 (8x12)	62	4	93,55%	5,49%

B. Conceptual framework for implementation of SPC



Figure_APX 9-1:framework spc

C. Systematic literature review

Systematic literature review

The systematic literature review will be done on the following knowledge problem:

'What is a suitable way to implement statistical process control at the end control on the attenuation measurement process.'

Defining the inclusion and exclusion criteria

Inclusion criteria

- The sources have to be scientific
  - Scientific sources are as reliable as possible due to for instance they are mostly peer-reviewed. Also looking at the number of citations gives somewhat of an indication of how scientifically respected the paper is.
  - It is objective with references to the sources used
  - Scientific sources are verifiable and replicable, making them as objective as possible.
- The sources must be in English (or Dutch)

  - It is important to understand the sources fully and it is also easy to have sources that do not need to be translated before accessing them.

Exclusion criteria

- Age limit
  - When a paper is relatively old, new papers may have been published having insights into the process and making the old paper less relevant. The paper must be published after 2000.
- Open access only (no closed access)
  - As it is not desired to pay for consulting literature, the non-open access papers are excluded.
  - Although a lot of papers are available through the UT find site and via the Lean Library Plug-in.

The databases used

The databases used are Scopus, Web of Science and arXiv.org. It is not smart to use search engines like Google scholar or Find UT because these search engines provide different results for every user. After all, the results are based on an individual's behaviour on the internet.

Scopus is a multidisciplinary database with a lot of papers and over 20 thousand peer-reviewed journals. Also, the web of science is a very big multidisciplinary database providing over 20 thousand peer-reviewed journals.

arXiv.org is a more specific database including papers with subjects in physics, mathematics, computer science, quantitative biology, quantitative finance, statistics, electrical engineering and systems science and economics. There is the possibility to only search in papers having a certain subject. As my research question is "what is a suitable way to implement statistical process control at the end control of the attenuation measurement process." It is important to search within the statistic's subject directory for papers.

Search terms and the used strategy

When searching on statistical process control there are a lot of articles coming up. Hence it was needed to narrow down the search. First, the paper needs to be related to statistical process control. Hence the article's title must contain the search strings. The search strings by making use of synonyms for a lot of words. Also using the truncation sign for finding search results including various types of the word.

Table_APX 9-2:Search strings and results

Search Number	Date of search	Search string	Searched in:	Used papers	Number of search results	Number of good results	Database	Comments
1.	04-11-2022	Statistical AND Process AND Control	Title	0	9	0	arXiv	This search is relatively restricted, most papers

								were about SPC applications in a different field.
s2.	04-11-2022	TITLE ((appl* OR adopt* OR practising OR implemen*) AND ((statistical AND process AND control) OR spc) AND production)	Title	2	21	2	Scopus	Found 2 sources and 1 duplicate, the same as for string 3
3.	04-11-2022	TITLE (control AND charts AND production AND (SPC OR (statistic* AND process AND control)))	Title	1	4	1	Scopus	Only the: "Application of statistical process control charts to monitor changes in animal production systems" gave a clear explanation of SPC and control charts.
4.	05-11-2022	TITLE (((statistical AND process AND control) OR spc) AND (tutorial OR impleme*))	Title	0	68	5	Scopus	A high number of sources, so it was not possible to go through all of them, however, found several good results but, did not

								have the time to go through them
5.	21-01-2023	Statistical AND process AND control AND improvement	Title, Abstract, keywords	2	1089	>20	Science Direct	A lot of interesting results only were not able to go through the full list.

Sources obtained from Strategic literature review

- Application of statistical process control charts to monitor changes in animal production systems1 A. De Vries*2 and J. K. Reneau† (use google scholar to access the source)
- Implementation of statistical process control methods as a way to reduce production costs and improve product quality
- Continuous Quality Improvement by Statistical Process Control, Procedia Economics and Finance2015...
- Statistical Process Control: No Hits, No Runs, No Errors? Thomas R. Vetter, MD, MPH,* and Douglas Morrice, PhD†(after snowballing)

conceptual matrix

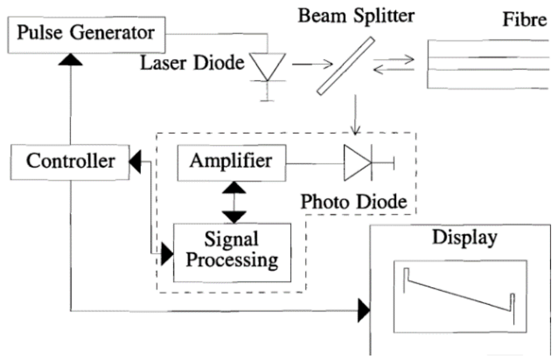
The conceptual matrix given below gives some explanation about what is included in the given papers below. Also, it gives which search string resulted in finding the given papers. The various subjects are: 'Introduction to SPC', 'explanation about different control charts', 'methodological or procedural', 'out of control procedure', and 'general statistical information'.

Table_APX 9-3: conceptual matrix

		Parts of the research included				
	Found with search string number	Introduction SPC	Various control charts	Methodological or procedural	(Out of control) procedure	Statistical information
(De Vries, 2010)	2,3	V				V
(Antony, 2003)	4	V		V		
(Gejdoš, 2015)	5	V		V		V
(Vetter, 2019)	5	V	V			V

D. OTDR measuring system explanation.

An Optical Time-Domain Reflectometer, OTDR, is a measuring instrument that is mainly used to obtain characteristics of optical fibres. Typical optical fibre elements are the fibre length and the attenuation coefficient. It is important for the fibre not to be perfectly uniform. It needs to have a small amount of non-uniformity, to make sure there is a constant behaviour of optical and physical fibre behaviour along the entire length of the fibre. The OTDR can transmit laser pulses through an optical fibre. The OTDR that measures attenuation at TKF is using light pulses with a wavelength of 1550nanometre and 1310 nanometre. There is a schematisation of an OTDR system given below. As one can recognize there is a laser diode generating laser light. After that, there is a beam splitter. This beam splitter makes sure the laser light gets sent into the fibre and the backscattered light from the fibre gets sent to the photodiode. The fibre given in this picture represents the fibre that is not necessarily there to be measured but enables a good coupling between the to-be-measured fibre and the OTDR measurement system. The backscattered light returning to the photodiode is of very low intensity. That is why the amplifier is used to magnify the scatters. The signal processing part gets rid of all noise. This is done by taking the average of an array of backscatter signals. The controller is used to process the backscatter signals and direct the pulse generator and the display. (Vullers, 1995)



Figure_APX 9-2: OTDR system

E. DMAIC steps

Rational reconstruction of the DMAIC procedure, after De Koning and De Mast (2006).

Define: problem selection and benefit analysis
D1. Identify and map relevant processes
D2. Identify stakeholders
D3. Determine and prioritize customer needs and requirements
D4. Make a business case for the project

Measure: translation of the problem into a measurable form, and measurement of the current situation; refined definition of objectives
M1. Select one or more CTQs
M2. Determine operational definitions for CTQs and requirements
M3. Validate measurement systems of the CTQs
M4. Assess the current process capability
M5. Define objectives

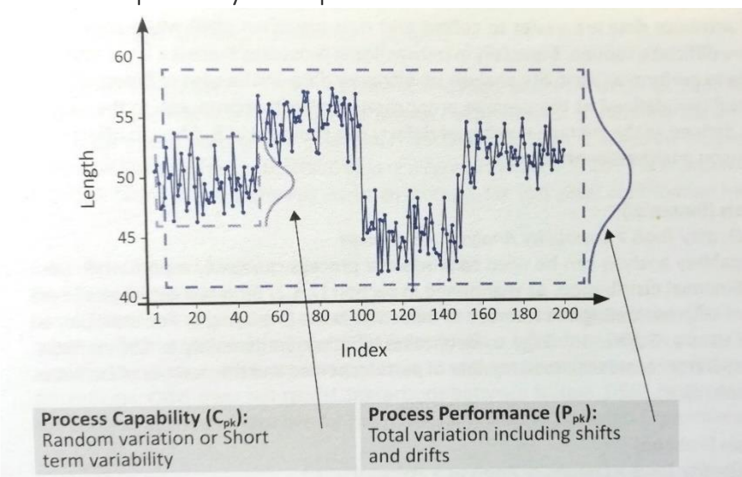
Analyze: identification of influence factors and causes that determine the CTQs' behavior
A1. Identify potential influence factors
A2. Select the vital few influence factors

Improve: design and implementation of adjustments to the process to improve the performance of the CTQs
I1. Quantify relationships between Xs and CTQs
I2. Design actions to modify the process or settings of influence factors in such a way that the CTQs are optimized
I3. Conduct pilot test of improvement actions

Control: empirical verification of the project's results and adjustment of the process management and control system in order that improvements are sustainable
C1. Determine the new process capability
C2. Implement control plans

Figure_APX 9-3. DMAIC steps

F. Capability and performance



Figure_APX 9-4. process capability and performance

G. Six sigma metrics

Table_APX 9-4. Six sigma metrics for a centred process

Sigma level	Specification width	ppm outside spec	Percent defective	Cp; Cpk
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	0.0000002%	2.00

H. Six sigma metrics with shift

Table_APX 9-5. six sigma process when incorporating a 1.5 sigma shift

Sigma level	Specification width	ppm outside spec	Percent defective	Ppk (long term)
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

I. Flowchart of failure handling processes

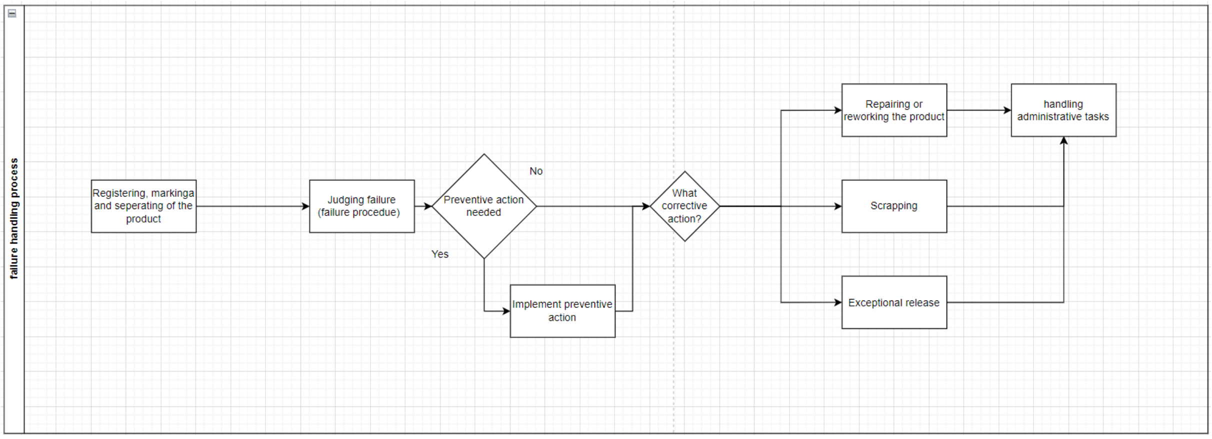


Figure 7.3-1.flowchart of failure handling process

J. Cable preparation for testing

Figure APX 9-5. fibre stripper

During the preparation phase, the cable gets stripped, and the coloured fibres become visible. After that, it is possible to lay them in the order given. The coloured fibres are placed in special casings, corresponding to the fibre diameter. After that, the fibres are undone from their identification layer, shown inFigure APX 9-5. Thereafter, the fibres get cut to the correct size. Subsequently, the fibres get placed into the multiple alignment system (MAS). This step could be viewed in Figure APX 9-6.

Figure APX 9-6. Attenuation measurement connection

Every casing contains a maximum of 12 fibres. The MAS fits ten cases, resulting in only being able to measure 120 fibres each round. Every fibre gets tapped by the measuring fibre. This fibre is connected to the OTDR machine. When the measurement fibre is connected to a single fibre, the attenuation will be measured, by making use of light pulses with two wavelengths: 1310 nm and 1550 nm.

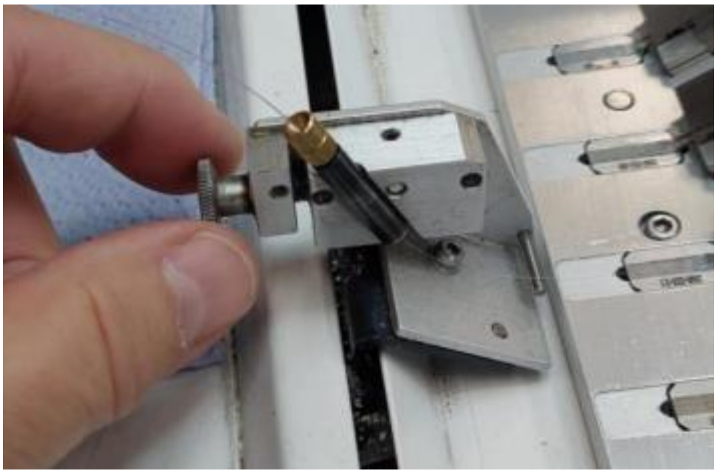


Figure APX 9-7. Measuring fibre on MAS

After the measuring fibre has measured all fibres, there is a probability not all fibres are passed through without issues. This is indicated by the notation NOK (not OK) on the screen of the OTDR. The fibres marked NOK will be measured again in the next round. Additionally, there is an out-of-control action plan (OCAP). This OCAP is used for finding solutions, when the connection between the measuring fibre and the to-be-measured fibre is not correct. A flowchart of the failure handling process could be found in Appendix I.

K. MSA results

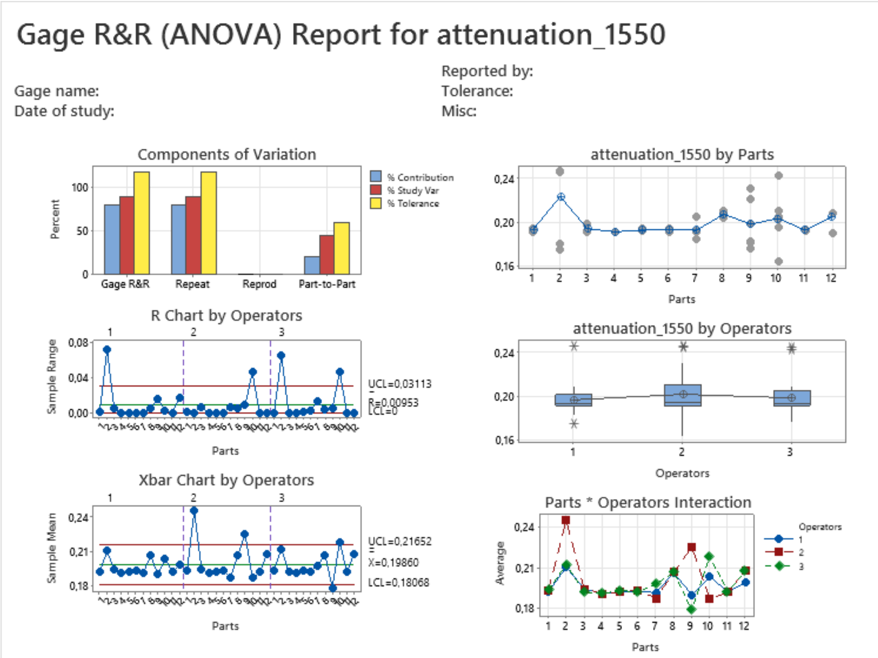


Figure APX 9-8 Minitab Gage R&R graphs (n=72; data for 13-12-2022; source:TKF)

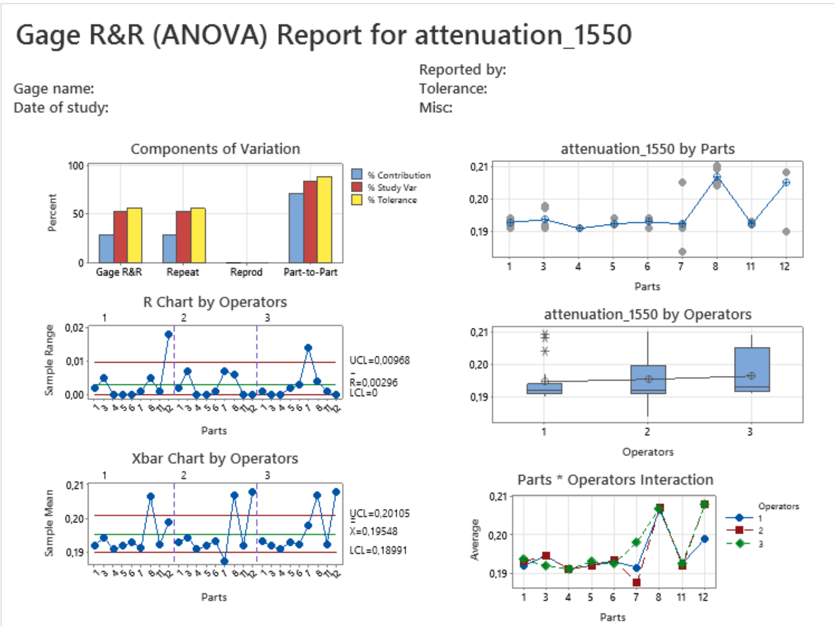


Figure APX 9-9 Minitab gage r&r ANOVA report when leaving out fibre 2,9 and 10 (n=54; data for 13-12-2022; source: TKF)

L. Process performance with control limits applied and without control limits applied

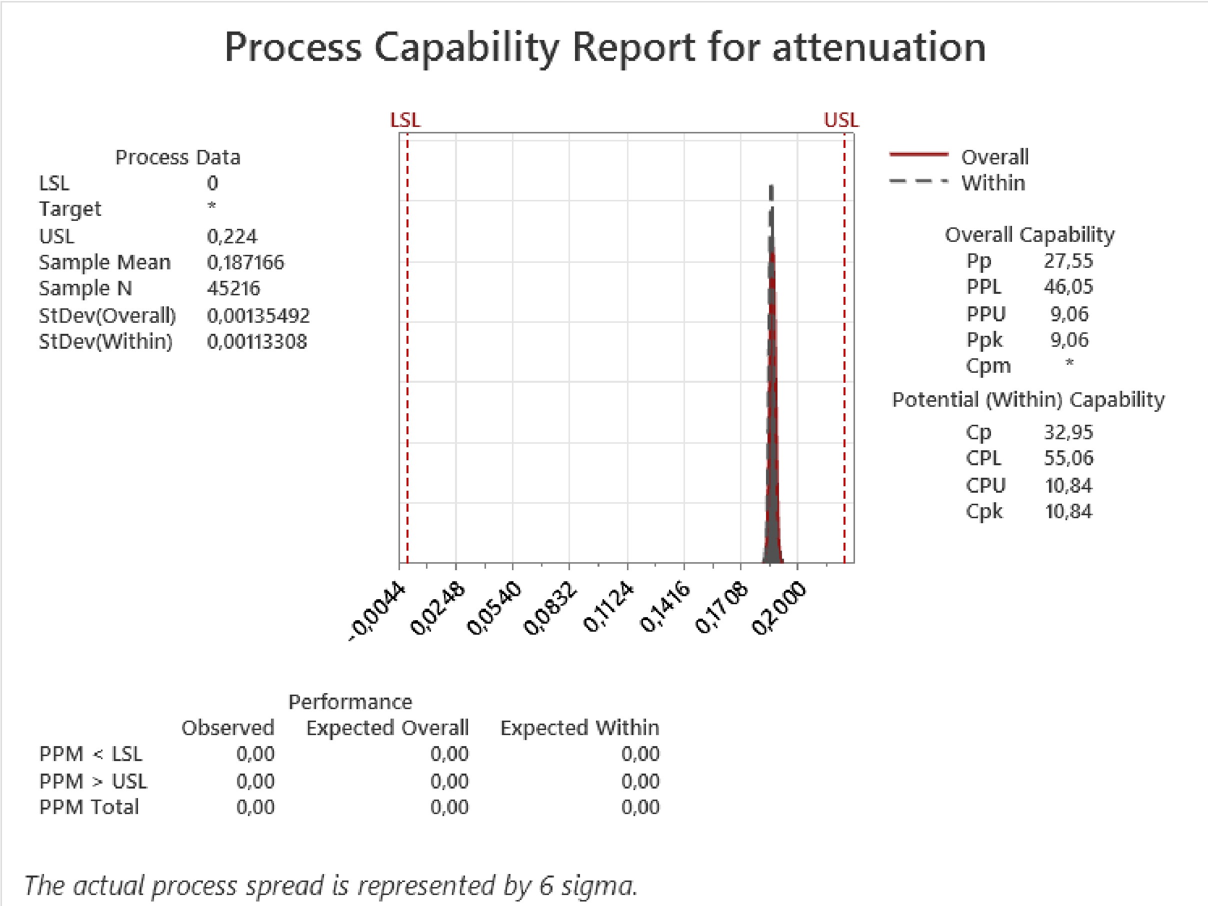
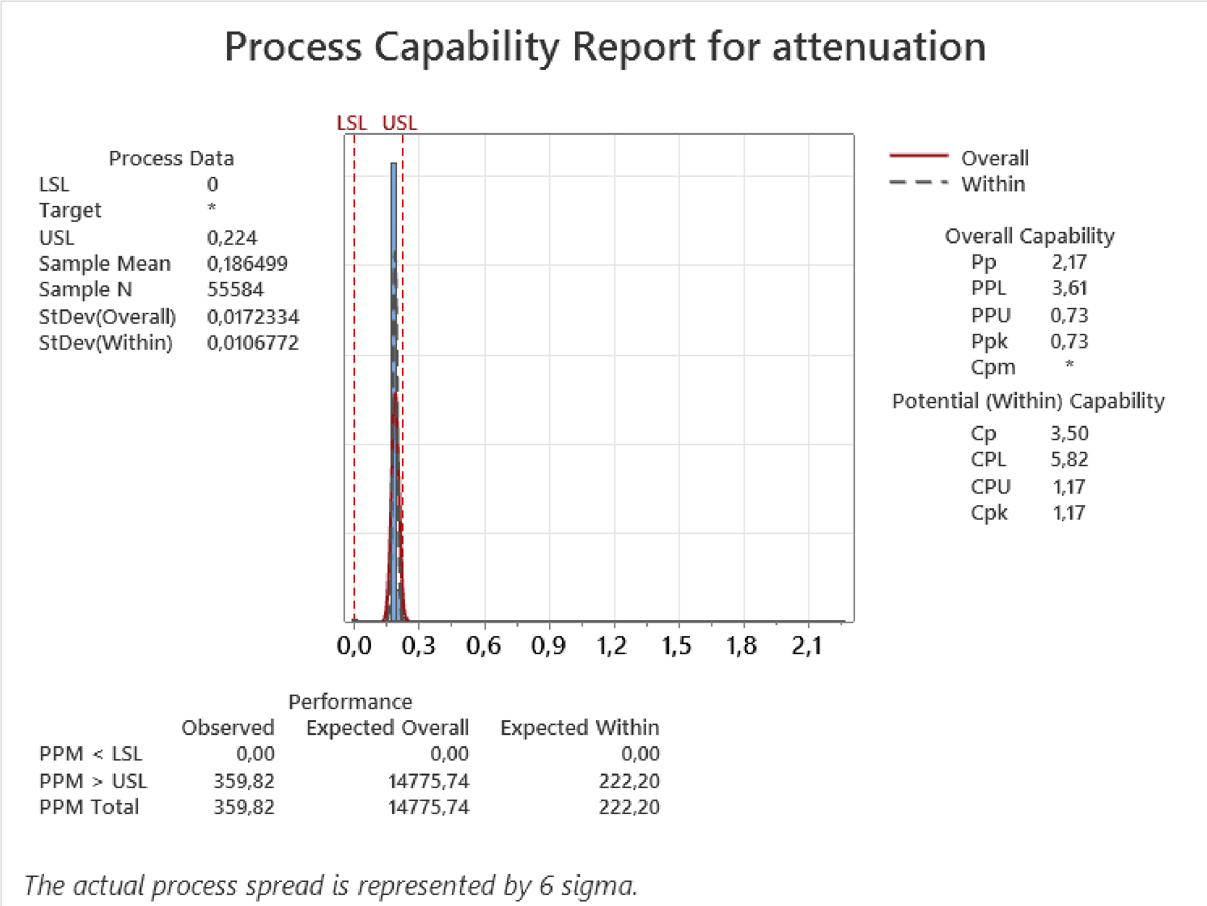
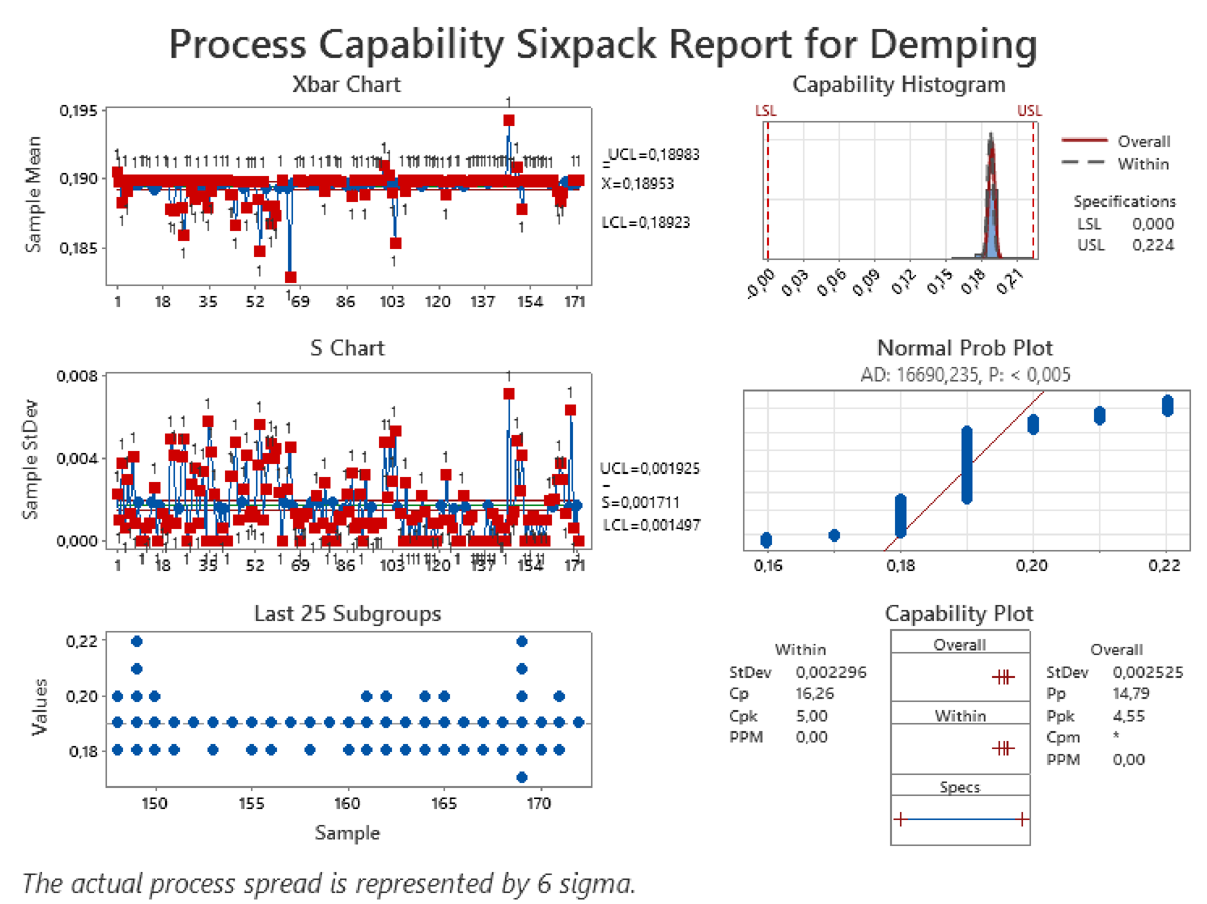


Figure APX 9-10. performance indices when control limits applied without outliers on 3rd measurement and 288-cable (n=45216; T=18-05-22/11-01-23, Source: TKF)



Figure_APX 9-11. performance indices when control limits not applied without outliers on 3rd measurement and 288-cable (n=55584; T=03-05-22/12-01-23, Source: TKF)



Figure_APX 9-12. Process capability report providing control limits (n=49536; T=12-05-22/11-01-23, Source: TKF)

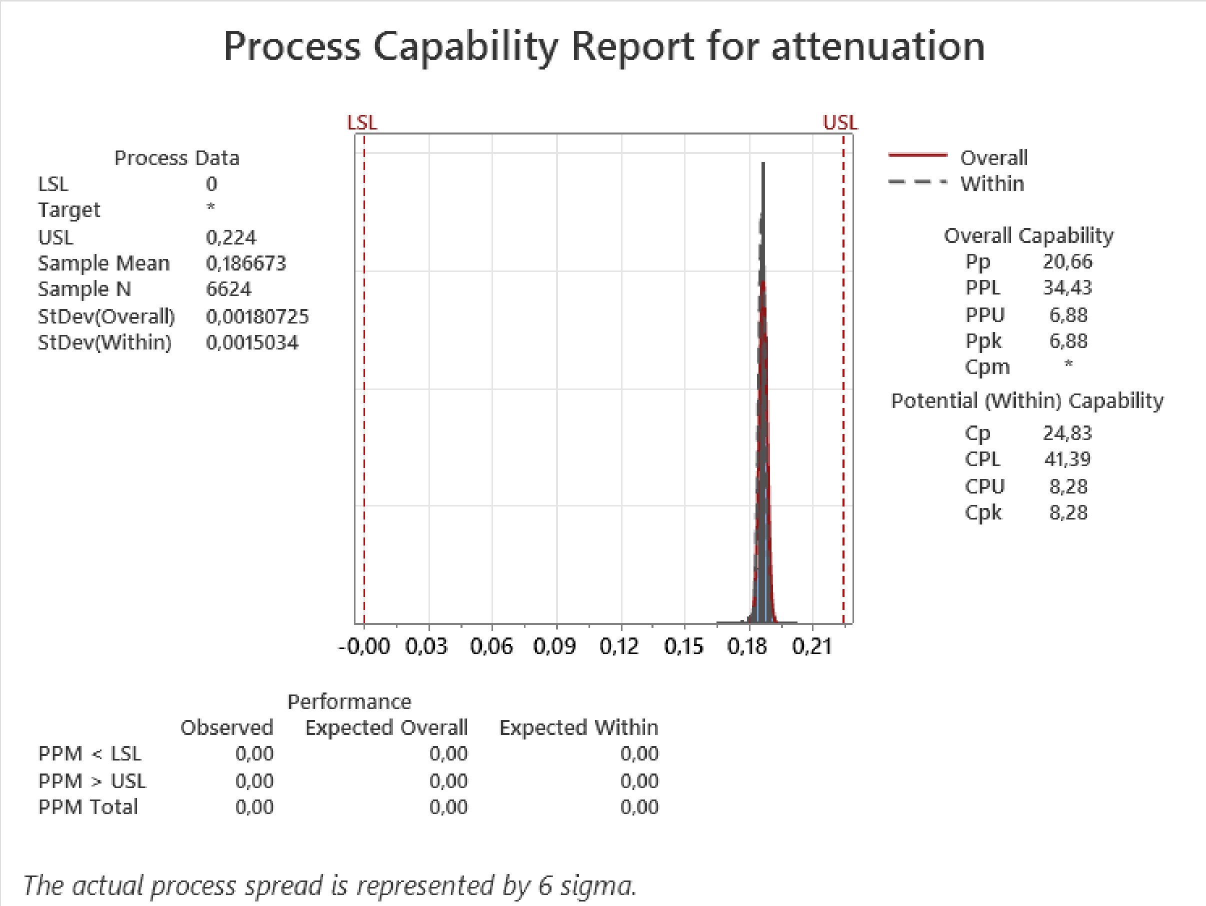


Figure APX 9-13. Process capability short term(n=6624; T=17-07-22/29-07-22, Source: TKF)

M. Cause and effect matrix filled for the different employees

Table APX 9-6. Cause and effect matrix

	rating of importance(1-10)>	5	7	10	
	Rating: 0 - no effect 1 - weak effect 3 - moderate effect 9 - strong effect	step in attenuation curve(trapje in dempingscurve) andre	attenuation is not as it should be (demping<>eis) andre	total signal loss at exit(andre)	total (andre)
main group	**KPIV**	**1st**	**2nd**	**3rd**	**total**
machines	Tubes in cable are longer than they are supposed to be	0	9	9	153
machines	Tubes have not enough lenght for the cable	0	9	9	153
materials	Reel core diameter is to small	0	9	9	153
materials	Lumps and necks higher spec limit	9	3	3	96
materials	Tube outside contains imperfections	9	3	3	96
man	Lining out the tubes correctly	0	9	3	93
measurement	Wrongly interpreted OTDR graph	3	9	0	78
materials	Tube inside contains imperfections	9	1	1	62
man	The tension of the 'dansers' is not correct	0	3	3	51
man	Tube guiding wheels not correctly alligned, not running smootly	0	3	3	51
materials	Diameter tubes not stable	0	3	3	51
man	Lining out the 'dansers'	0	3	3	51
man	Displacement of cable on a reel is to small	0	3	3	51
man	Displacement of cable on a reel is to big	0	3	3	51
materials	Diameter tubes to small	0	3	3	51
materials	Tube stick to outer sheath	9	0	0	45
materials	Tape is not able to completely enclose tubes	9	0	0	45
mother nature	Cooling routing is not sufficient for adequately cooling the cable	0	1	3	37
materials	Diameter tubes to big	0	3	0	21
man	Fixed end is not correctly attached	3	0	0	15
materials	Yarn is polluted	3	0	0	15
machines	Displacement of tube to big	3	0	0	15
machines	Winding up tension to low (sec6)	3	0	0	15
machines	Winding up tension to low (sec9)	3	0	0	15
materials	Granulate polution on sheathing line	3	0	0	15
man	Beginning piece incorrectly attached	1	0	0	5
materials	Tape induces pollution	0	0	0	0
materials	Application of yarn is not done correctly	0	0	0	0
machines	Insufficient Jelly/oil usage in the tube	0	0	0	0
machines	Jelly/oil flow is not stable enough	0	0	0	0
machines	Displacement of tube to small	0	0	0	0
machines	Winding up tension to high (sec6)	0	0	0	0
machines	Winding up tension to high (sec9)	0	0	0	0
man	No clean working environment on the sheathing line	0	0	0	0

N. Constants for control charts calculation

Table_APX 9-7 Constants used for control charts

n	C4	A3	B3	B4
2	0,797884561	2,658681	0	3,266532
3	0,886226925	1,95441	0	2,56817
4	0,921317732	1,628103	0	2,266047
5	0,939985603	1,427299	0	2,088998
6	0,951532862	1,287128	0,030363	1,969637
7	0,959368789	1,181916	0,117685	1,882315
281	0,999107543	0,179125	0,87317	1,12683
282	0,999110718	0,178806	0,873396	1,126604
283	0,99911387	0,17849	0,873621	1,126379
284	0,999117	0,178175	0,873845	1,126155
285	0,999120107	0,177861	0,874068	1,125932
286	0,999123193	0,177549	0,874289	1,125711
287	0,999126258	0,177239	0,874509	1,125491
288	0,999129301	0,176931	0,874728	1,125272
289	0,999132323	0,176624	0,874946	1,125054
290	0,999135324	0,176319	0,875163	1,124837
291	0,999138304	0,176015	0,875378	1,124622

The constants in this table are calculated by making use of the following equations. Where n is the subgroup size("xbar and s control chart," 2021).

$$C4 = \frac{(n/2) * \sqrt{2/(n-1)}}{((n-1)/2)}$$

$$A3 = 3/\left(C4 * \sqrt{n}\right)$$

$$B3 = 1 - \frac{3\sqrt{1 - C4^2}}{C4}$$

$$B4 = 1 + \frac{3\sqrt{1 - C4^2}}{C4}$$