Critical diameter measurement of washers

A Six Sigma process improvement project at SKF, Gothenburg

by

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Cover:
A dismantled spherical roller thrust bearing. The black double sided arrow indicates the critical inner diameter that is being measured in the measurement process discussed in this report.

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SUMMARY

The LT5 production line at the SKF factories in Gothenburg manufactures and assembles spherical roller thrust bearings in various sizes. One component in this product, the lower washer, has lately often been found to have very varied shaft diameters. This measurement is crucial to the performance of the washers, and thereby for the customers.

There were however speculation that the bad results are not entirely due to the production of the washers but may also be caused by a poorly performing measurement process. The measurement process that consists of two measurement stations that seems to get rather varied results despite measuring the same thing. Managers as well as operators in the LT5 channel initially thought that this could be due to the way dimensions change based on the temperature of the material – something that was taken into consideration, but perhaps with the wrong formulas?

This thesis has proven that the formulas used were correct, but confirmed that the measurement process performs very poorly. Many types of waste can be observed in the process; for example waiting, transportation and defects. The idea of having two measurement stations measuring the same thing is also a waste, but nonetheless they should (including temperature compensation) receive the same values when measuring the same dimensions. The problem has also been proven not to be due to the measurement tools themselves – but rather the way the tools work in the real world. Their sensitivity to human error as well as environmental effects such as metal shavings getting in the way of the measurements is the reason for the issues.

The result of this thesis, apart from the reassurance that the temperature of the material is accounted for correctly, is a collection of recommendations that can improve the situation. The process can be made more effective and insensitive to these types of variation by introducing new tools both for the measurement of diameters and temperatures, as well as adding computer aided calculations where possible. By entering the measurement values into a computerized system also allows the production channel to add means of controlling both the production and the measurement processes' performances over time.

Keywords: Six Sigma, process improvement, measurement process

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1. INTRODUCTION

Measurements and other means of controlling the quality of a product is something that largely can be considered a wasteful activity as it in itself does not add any value to what is produced. The need for measurements is a sign of problems elsewhere in the process chain, but sometimes the cost of removing these issues can be higher than to "just measure" – making the measurements a necessary evil. A cleverly designed measurement process can also provide great knowledge into the production process preceding it. Without this knowledge it might be impossible to improve other involved processes.

This thesis is about how to gain the maximum benefits out of one of these necessary measurement processes.

1.1 Background

The SKF company group was founded in 1907 and has since grown to become the world leader in the fields of bearings, mechatronics and lubrication systems as well as related service fields. The group in its entirety employs about 40,000 people – 3,100 of these in Sweden. SKF Sverige AB is responsible for the production of spherical roller and ball bearings.

Figure 1.1: A spherical roller thrust bearing (SKF AB, 2011).

This thesis concerns the production and quality control of spherical roller thrust bearings (SRTB) that are (partially) produced & assembled by the LT5 production line (or channel) at the large bearings factory in Gothenburg. These bearings come in several different sizes, with inner diameters from Ø160 mm to Ø420 mm, and have very strict tolerances especially concerning this crucial inner shaft diameter. Recently the production line was relocated and a new hard turning machine acquired and since then quality issues have surfaced. Directly after the hard turning process several measurements are carried out to ensure that the machined washers adhere to the specifications. This measurement process is vital to finding the solution to any problems in the hard turning process itself.

The quality of this measurement process has however been questioned. It appears that, for example, diameter measurements taken early in the process do not match diameter measurements taken later – possibly implying that the way the dimensions of the washers change based on their temperature is not accounted for accurately.

1.2 Purpose

The purpose of this thesis is to investigate the measurement process following the hard turning in the production channel LT5, determine the current process performance as well as the main factors hindering the process. Part of the investigation should ensure that the dimension change of the products due to temperature is being calculated correctly.

Should the process performance require improvements, these are to be identified and prepared for implementation.

1.3 Delimitations

This thesis will only look into the process that can be said to start as the hard turning operation on a washer is completed and end at the final decision that the washer is accepted or rejected.

1.4 Report structure

Initially the relevant theories that the reasoning in this thesis is based upon are covered (Chapter 2). Subsequently follows a description of any methods used in the investigation and analysis of the problem (Chapter 3).

The main part of the report (Chapter 4) follows the Six Sigma project structure: Define, Measure, Analyze, Improve & Control (Chapters 4.1 – 4.5).

The final chapter (Chapter 5) concludes the report with a discussion about the results as well as reflections upon the work carried out.

2. THEORY

This chapter introduces and explains the theories considered throughout this thesis.

2.1 Six Sigma Basics

Six Sigma is an improvement program that is based on the strategic initiatives taken by Motorola in the late 1980s and forward. Since then many companies, all across the world, involved in many different fields from the traditional industry (such as automotive, chemical & electronic) to healthcare have adopted (and adapted) the methods in order to improve (Magnusson, Kroslid, & Bergman, 2003). Many of these, but far from all, endeavors seem to have been successful leading to a stronger customer focus, an understanding of variation and its effects, decisions based on facts and better communications regarding quality issues.

One of the cornerstones of most, if not all, Six Sigma initiatives is the training programs that educates members of the organization in the use of methods and tools useful for quality improvement work (Bergman & Klefsjö, 2001). Often, the members are given different titles based on the amount of training they receive ranging from white belts and green belts (that usually take the Six Sigma responsibilities as an addition to their daily work tasks) to black belts (sometimes full time improvement leaders), master black belts and champions that usually reside higher in the hierarchy of the organization, able to provide resources and guidance.

The meaning of “Six Sigma”

The focus of Six Sigma is the reduction of unwanted variations that can be very costly both in economic terms and as they potentially leads to unhappy customers (Bergman & Klefsjö, 2001). The symbol σ (sigma) stands for the standard deviation – a measure of how close to the mean the observations are for a population. A process with a low σ will have most observations close to the mean, while a high σ will lead to a more spread out result.

Bergman & Klefsjö (2001) states that for a process within statistical control, and a normal distribution to the output, the distance between the process mean to the closest tolerance limit be at least six times the process standard deviation, σ (hence, Six Sigma). Processes are however never perfect, and are perhaps always affected by systematic variation. According to the Six Sigma way of looking at things, a deviation of no more than $\pm 1.5\ \sigma$ is acceptable leaving a distance to the nearest tolerance limit no less than $4.5\ \sigma$. This means that the risk of the outcome to be “unfavorable” (outside the tolerance limits) is never above 3.4 in one million.

The core of Six Sigma is the ability to reduce unwanted variation by looking at measureable characteristics – and by doing so reducing measurable costs, alternatively increasing customer satisfaction.

How to work with Six Sigma

The Six Sigma procedure is a cyclic process with much in common with the classic PDCA-cycle (Plan, Do, Check, Act). Similarly this process consists of a set of stages: Define, Measure, Analyze, Improve & Control (DMAIC) (Magnusson, Kroslid, & Bergman, 2003). The define phase focuses on trying to determine what it is that the project will look at and what outputs that it will try to improve (“the y’s”). The measure phase then continues in mainly identifying the inputs to the process that affects said outputs. Data collection plans and similar are developed and pursued at this stage. Analyze then uses various methods in order to understand the outputs better as well as learning how the inputs identified earlier affect the outputs. In the improve phase the information and knowledge gathered in the earlier steps is utilized to find or design solutions to the problems, determine what solution is the best and subsequently implement that solution. Finally, the success of the project is determined in the control phase. This last step is also about reflection upon the way the project was carried out, and communicating any new knowledge to the rest of the organization.

Each phase is generally connected to a set of tools (often standard quality area methods) taught at Six Sigma training seminars, held internally, by specialized companies or by universities. The specific tools, although varying from organization to organization, provide a solid base for each project.

2.2 Lean

Lean thinking is the basic idea that there are two types of activities: those that create value, and those that do not (Womack & Jones, 2003). “Value” itself can only be truly defined by the end customer, as it is this customer that pays for the product or service that the supplier provides. Waste on the other hand can take on many forms, often called the seven wastes: overproduction, excess inventory, waiting, transportation, unnecessary motion, over processing and defects (Wang, 2011).

Lean thinking is about removing these wastes and thereby more accurately providing what the customer wants, but using fewer resources in doing so. It is important not to lose that customer focus – the best measure of “quality” is the degree of customer satisfaction (Bergman & Klefsjö, 2001). The starting point for a lean mindset is therefore to be able to define value (Womack & Jones, 2003) and the key to lean thinking is the ability to connect each process step to the desired customer experience.

Lean and Six Sigma are often used together (frequently called Lean Six Sigma). This can be very fruitful thanks to Six Sigma’s focus on reduction of variation – the coping mechanisms for variation are often the reasons behind many of the seven wastes (Wang, 2011); perhaps especially inventory, overproduction and defects.

Tools and techniques often used for Lean applications include moving from push to pull systems, reductions in set-up times (SMED, Single Minute Exchange of Die), continuous improvements, 5S and Value Stream Mapping (VSM) (Wang, 2011).

2.3Turning

Turning is a very flexible means of shaping rotationally symmetrical work pieces into the desired shape (Jarfors, Carlsson, Nicolescu, Rundqvist, Keife, & Eliasson, 2000). The turning is a combination of two actions: the rotation of the work piece and the movement of the tool. Because of the forces involved large amounts of heat may be a byproduct of the process leading to a need to use fluid coolants (cutting fluids). These may be water or oil based and, besides cooling the work piece and tool in order to prevent measurement variations and overheating, they can also serve lubrication purposes or to transport removed material from the turning area.

There are many factors that can affect the end result of the turning, such as rotational speed, depth of the cut, tool geometry as well as temperature fluctuations. Different materials therefore naturally need different settings.

Hard turning is as the name implies turning used on very hard materials, usually as a final step in the production (Koepfer, 2010). The method is cheaper and faster than competing alternatives such as grinding. Compared to “softer” turning the demands on a vibration free environment with stable machinery are often higher in order to reach good results.

2.4Thermal expansion

Heating a material will cause it to change in volume (Groover, 2010) due to decreasing density; this is called thermal expansion. While this effect can be used beneficially in for example shrink fitting, it is generally a problem as it can lead to changed geometry or built in stress. The change is most often measured as a length rather than a volumetric as that is more convenient. This change in length is described by

$$L_2 - L_1 = \alpha L_1 (T_2 - T_1)$$

where α is the coefficient of thermal expansion, which varies depending on the material and L_1 and L_2 are lengths corresponding to the temperatures T_1 and T_2. This is only an approximation, as the lengths themselves as well as the coefficient changes based on the temperature.

2.5 Relevant terms in research and experimentation

There are many terms and concepts that are important to know and take into account when doing research and experimenting. When gathering information it is naturally important that the appropriate things are investigated, high validity, and that good methods are used, high reliability (Davidsson & Patel, 2003).

Validity can be seen as the measure of how well a measure actually describes the occurrence or item it is said to describe (Bryman & Bell, 2007). For example the height of a tree is a less valid measure of the age of the tree than the counting of growth rings.

Reliability refers to how well the chosen method performs in measuring the occurrence it is supposed to measure. It can be divided into three sub-categories (Bryman & Bell, 2007): stability, internal reliability and inter-observer consistency. Stability, or repeatability, refers to the concept of being able to repeat the same experiment and get the same results, given that the conditions are the same. Internal reliability is the measure of whether or not several indicators can be connected to the same conclusion or not. Finally inter-observer consistency usually means how well the subjective observations of two observers agree, but in a more quantitative setting reproducibility is also part of this. Reproducibility indicates how the same experiment can be carried out by other people, with different equipment, and so forth, but still obtain the expected, comparable, results.

2.6 Ergonomics

It is common knowledge that work related injuries are common among those who work with transport and handling of goods in the industry (Rislund, 2006). The problems can be caused by heavy lifting or work in unhealthy positions. People who handle material are affected three times as often, compared to the average, by strain related injuries. These types of injuries often result in long term sick leaves. Most serious accidents happen during loading, unloading or carrying of goods.

In cases where manual lifting is necessary it is best to place things in the “Golden zone”, between 75 and 140 centimeters from the ground.

2.7 Stress

Stress is a natural reaction that is induced when a human needs to get a lot done and has high demands placed upon him/her (Perski, 2010). The stress gives more power and energy in order to allow the person to perform difficult tasks, but if a person experiences stress on a regular basis when it is not necessary it can lead to problems such as headaches, tiredness, sleep issues and worsened memory. In the worst cases it can lead to breakdowns and fatigue syndromes.

In order to lessen the stress it is important to create an environment where the work that is carried out is seen as meaningful and that the situation is possible to affect if necessary. On the other hand, if the work is seen as unimportant or difficult to change it can be seen as extra stressful.

3. METHODS

This chapter describes the methods used during the thesis work.

3.1 Methods for gathering data

Data can be collected in countless ways but all data collection can be classified into either qualitative or quantitative research (Davidsson & Patel, 2003). Qualitative research focuses on the experienced feeling, an example being interview questions taking into account the interviewee's interpretation of the situation and view on life. Quantitative research on the other hand cares only for the "hard data", for example exactly how many employees that agree on one specific item.

When involving people in data collection it is of vital importance to assure that they are motivated and truthful (Davidsson & Patel, 2003). This can be done by for example sharing the purpose of the investigation or guarantee anonymity. Another problem when studying people, or what they do, is that they may change their behavior as they feel under scrutiny.

The following sections will briefly describe some of the basics regarding two of these methods. More information regarding more specific, experiment based, methods can be found later in this chapter.

Interviews and questionnaires

Interviews and questionnaires are two very similar methods, both based on questions (Davidsson & Patel, 2003) either orally or by text. The degree of structure and standardization are two characteristics that are important. Standardization meaning the liberty that the interviewer has to modify the questions, ask other questions or to simply make up questions on the go. Structure means the degree of freedom that the interviewee has in the answers. Naturally, questionnaires generally have a high standardization and structure as both the questions and the answer options often are predetermined for all participants.

Observation

In everyday life observation is the most common method for data collection and is done both consciously and subconsciously and often at random (Davidsson & Patel, 2003) but in the scientific setting it is often done in a more controlled fashion. As with the question-based methods the degree of structure is important for the data collection. A high structure in this case could mean for example using a check-list for certain occurrences, while a low structure would mean trying to register "everything" that happens (while still focusing on the aspects important to the task).

3.2 SIPOC

SIPOC (short for Supplier Input Process Outputs Customers) is a diagram or table shaped tool that allows the user to determine the scope of a project including stakeholders as well as what people and resources will be affected by the work (Hammersberg, Lecture: Project charter - High level process map - SIPOC, 2011). The SIPOC is especially useful when it is unclear who the suppliers of the process inputs are and what requirements exist on these inputs or who the customers of the process really are and what their requirements are (Simon, 2010). The broad overview of the process that the SIPOC gives is also useful in that it unites the project team and provides a shared vision of the situation (Hammersberg, Lecture: Project charter - High level process map - SIPOC, 2011).

Creating the SIPOC is ideally done by a team of people with viewpoints that cover the entirety of the project – such as green belts, black belts, process owners and even customers. As mentioned earlier the tool resembles a table with the headlines Suppliers, Inputs, Process, Outputs and Customers. This can be seen in Figure 3.1.

Suppliers	**Inputs**	**Requirements**	**Process**	**Outputs**	**Requirements**	**Customers**
(6)	**(5)**	**(7)**	**(4)**	**(1)**	**(3)**	**(2)**

Figure 3.1: A very basic example of a SIPOC table.

The steps of filling the SIPOC table with information is as follows (Hammersberg, Lecture: Project charter - High level process map - SIPOC, 2011): Firstly, the outputs of the process are identified (1), and then the customer for each output is determined (2) as well as their requirements (3). Subsequently the process is outlined (4) and finally the inputs needed (5) are listed as well as who supplies them (6) and what the process' requirements upon these inputs are (7).

3.3 Process mapping

Process Mapping is a flowchart used to identify how a process really works and includes all significant information that are relevant to the project. It helps to simplify complex processes and also show non-value-added processes. The user can visually describe any process using the inputs and outputs in each step of a process (Hammersberg, Lecture: Qualitative Mapping and Funneling for X-factors, 2011). Process mapping can be illustrated by the formula $Y = f(X_1, X_2, X_3, X_4, \dots, X_n)$, where the x's represent the process inputs and the Y is the output of the process.

The benefits of process mapping for the user is to describe the major activities/tasks and its variables connecting to specifications, bottlenecks, reworks as well as customer expectations and suppliers (Hammersberg, Lecture: Qualitative Mapping and Funneling for X-factors, 2011).

The process mapping is done in four steps (Sörqvist & Höglund, 2007). It starts by listing each process step, followed by all outputs for these steps, and thirdly the inputs for each step. While this is very much like the SIPOC it is generally done in greater detail and with the difference that the P-map only handles what happens inside the process whereas the SIPOC handles what surrounds the process. The last step is the crucial point of the process mapping: each input is given a classification that will help determining how to tackle the problems affecting the process. There are four different classifications: controllable (C), noise (N), standard operating procedures (S) and critical (!). The inputs can be classified as both critical and one of the other classifications at the same time (ex. C!, or N!). Controllable inputs can be changed in order to affect the output (for example machine settings), noise represents things that are uncontrollable or very difficult to control (such as environmental variables) and standard operating procedures are core activities that are required for the performance of the process task. The critical classification is given to inputs that are believed (preferably known) to have a great importance for the output quality.

3.4 Potential Failure Mode and Effect Analysis (PFMEA)

Failure Mode and Effect Analysis, FMEA, is a tool used to identify different ways that things can go wrong and rate the severity of the occurrence (Hammersberg, Lecture: Potential Failure Mode and Effect Analysis (p-FMEA), 2011). Doing this allows ordering said failures based on their severity and likelihood and thusly allowing for focused efforts in eliminating risks. One of the strong points of using FMEA is that it documents and standardizes the information that decisions are based upon giving both a good traceability of actions and a good tool for communicating the reasons for these actions.

The FMEA can be said to be made up of six steps (Sörqvist & Höglund, 2007). Firstly, all the process steps are listed – they can be extracted from the process map or a cause and effect matrix. Thereafter all the possible ways these steps can go wrong are listed; these are the failure modes. For all these failure modes the effects, causes and controls are described. Finally each failure mode is given a severity, an occurrence and a detectability number that can be multiplied to calculate the risk priority number. Severity is a number indicating how dangerous or costly a failure is, occurrence indicates the probability of the failure happening and finally detectability is a measure of what, if any, means for control and mitigation that are currently in place.

Potential FMEA works in the same way as a regular FMEA but with the addition of also including a proposition on how to minimize the risks, and providing a new priority number. Generally, the generation of these improvement propositions can be traced back to either the severity, occurrence or detectability ratings (Hammersberg, Lecture: Potential Failure Mode and Effect Analysis (p-FMEA), 2011). A high severity rating is often hard to improve and requires design changes. Reduction in occurrence generally involves process or design changes. The detectability can often be improved by implementing better control, or preferably prevention measures.

3.5 MSA/Gage R&R

Measurement System Analysis (MSA) is a type of experiment specially designed to determine contribution of different sources of variation to the overall variation of measurement results. The axiom lying in the base of MSA is that a true value of a variable is unknown and unknowable, so any measurement is just a comparison of a value with some reference. The process of comparison itself includes variation in terms of consistency, which might result in different values of measured variable. One of the most commonly used tools to assess a measurement system is Gage R&R.

The purpose of Gage R&R study is to examine the variation of measurements and to assess the level of influence of different factors on this variation. Two main factors for this assessment are repeatability and reproducibility. Repeatability represents the probability that the same person will achieve the same measurement value for the same variable over and over again, while reproducibility stands for the probability that different operators will obtain the same results measuring the same variable. Another important contributor to the measurement variation is the part-to-part variation, which represents the natural variation of variable between several measured objects.

To assess these types of variation a Gage R&R study usually consists of several repetitions of measurements performed by several operators on several objects. The amount of objects, operators and repetitions needed depend on the desired level of result reliability and acceptable costs. Usually these aspects are determined by a Quality Engineer. A very important issue to consider is the randomization of experimental runs. This is applied in order to avoid results misinterpretation, which can be caused by some external factor affecting the measurement process but not controlled or kept track of.

Total Gage R&R is a percent of results variability due to the lack of repeatability and reproducibility. There are a number of different sources of variation which can be examined with a Gage R&R studies, they are presented in the Table 3.1. Each of these contributors can be calculated separately, thus making it possible to evaluate the measurement system. Commonly used guidelines for evaluation of total Gage R&R (Barrentine, 1991) are as following:

- <10% - excellent;
- 11% to 20% - adequate;
- 21% to 30% - marginally adequate;
- >30% - unacceptable.

Table 3.1: Explanation of terms and abbreviations.

Variances Sums	**Term**	**Abbr.**	**Alternate Term**
V(Within)	Repeatability	EV	Equipment Variation
V(Operator)+V(Operator*Part)	Reproducibility	AV	Appraiser Variation
V(Operator*Part)	Interaction	IV	Interaction Variation
V(Within)+V(Operator)+V(Operator*Part)	Gauge R&R	RR	Measurement Variation
V(Part)	Part Variation	PV	Part Variation
V(Within)+V(Operator)+ V(Operator*Part)+V(Part)	Total Variation	TV	Total Variation

However, it is important to note that Gage R&R studies address only precision of a measurement system but not its accuracy. Another commonly used indicator is a P/T ratio which stands for ratio of measurement system precision to the tolerances which a part should adhere to.

3.6 Decision matrix (Pugh matrix)

A decision matrix, often called a Pugh matrix from its inventor Stuart Pugh (Thompson, 2007), is a method that evaluates a set of solutions based on how well it performs in a series of criteria (Tague, 2005). The matrix is mainly useful for two tasks: making a choice between a few solution options and finding the strong points of each solution and thereby starting a discussion on how to incorporate these advantages in whatever solution is chosen.

The procedure of using the decision matrix is rather straight forward. The criteria to be used need to be found (by, for example, brainstorming) and discussed. The criteria should at this stage be given a relative weight indicating its importance to any stakeholders. One way of doing this is by distributing a set amount of points among these measures (Tague, 2005). Each solution can now be compared to each criterion by multiplying the weight with an estimate of how well the solution would perform.

An example: Two solutions (1 & 2) are compared on three criteria (A, B & C), see Table 3.2. To estimate the weight of the criterions 10 points are divided between them. Criterion A is given the weight 5, B 3 and C is considered the least important and is given 2. Both solutions are given a value on a scale from 0 to 4, where 0 does not fulfill the criteria at all and 4 fulfill it completely. This value is multiplied with the weight for each criterion and this product is noted in the column marked "Total".

Table 3.2: Example of a decision matrix.

	Solution 1			**Solution 2**		
	Weight	Value	Total	Weight	Value	Total
Criteria A	5	3	15	5	4	20
Criteria B	3	4	12	3	1	3
Criteria C	2	2	4	2	2	4
Sum			**31**			**27**

Finally, all products are added and the sum noted at the bottom of the table. In this example it is clear that Solution 1 is somewhat better than Solution 2. However, the possibilities of incorporating Solution 2's method of handling criteria A into Solution 1 should be investigated, as that would make a better overall result.

3.7 Bivariate fit

Bivariate fit is a statistical tool for correlation analysis. It can be used to detect presence of correlation between two or several variables. Paired data is plotted on an XOY axes using one variable as an X coordinate and the other variable as Y coordinate. After that a linear regression line is made between the points. Linear regression line is modeled from the data using linear functions and estimating the unknown model parameters from the data. There are many ways to approximate the linear regression line from the data, but the most commonly used is the least squares approach. The solution should minimize the sum of squares of deviations of each single dot from the regression line. There are two main categories of applications of linear regression:

- It can be used to assess the strength of correlation between the variables;
- And it can be used to build predictive models for forecasting the behavior of one variable depending on the other variable value.

In this report it will only be used for correlation analysis, thus no elaboration on the predictive models usage will be provided.

A linear regression line slope represents the correlation coefficient. So if the line is flat, it means that no correlation between variables exists; the closer the line is to 45 degree, the more likely the data is dependent. However, it might be troublesome to base conclusions about cause and effect relations between the variables on the regression line slope. For example, if both variables are dependent on a third one which was not taken into consideration, the regression line can show a presence of correlation between them, which is in its nature a correlation between each of two variables and the third one.

4. THE MAIN PART OF THE REPORT

This chapter details the work carried out during the project. It follows the Six Sigma procedure, being divided into five phases: Define, Measure, Analyze, Improve and Control.

4.1 Define

The define phase of any project revolves around determining why it is necessary (i.e. what the problem is), understanding the process, how to and who should do these things, and often also what outputs (y's) are important and how they are measured (Magnusson, Kroslid, & Bergman, 2003).

In this project these points are answered through several steps. Before anything else, a project charter was prepared. This document (that can be seen in Appendix 4.1-1) contained the necessary information about the project, such as members and other resources needed for its completion. The charter was later updated as the project progressed and new knowledge was acquired. To start the project a description of the problem as it is seen by those already knowing and working with the process, followed by an in-depth description of the process, including a process map, helps with understanding the process as well as determining what is wrong with it. Finally a SIPOC was constructed to further help with the understanding of the process and any shortcomings.

Description of the process

The LT5 channel produces spherical roller thrust bearings with the inner diameter range from 160 to 420 mm. Operations performed at the LT5 channel include hard turning of the washer, polish of some washer surfaces (not in the shaft bore) and the final assembly. Due to the inconsistency in the hard turning process in terms of inner diameter variation, 100% of machined washers are checked for the adherence to the specification. Measurements are performed manually, without retrieval of the washer from the hard turning machine through a special window, which allows the operator to access the washer. In case of the inner diameter falling out from the specification range due to insufficient turning, the washer is treated further on until the next measurement confirms its correspondence to the specification. On contrast, if the inner diameter is bigger than the specification allows, the washer is considered to be scrap and is sent to recycling. As the hard turning process involves considerable warming of the washer, a fluid coolant is used to keep the temperature down to an acceptable level. However, the temperature of the washer differs rather accountably from the room temperature, and that leads to the need of including the heat compensation at the moment of inner diameter measurement.

The measurement process is based on a comparison of so-called master ring (a piece with a known value of the inner diameter, which is close to the target value) and the machined washer. Comparison is made with the use of two tools: a digital thermometer and an internal caliper, which is internally called the "SUBITO". From here on the gage for the inner diameter measurement will be called the SUBITO. Comparison is made in six steps:

1. SUBITO calibration: the SUBITO is inserted into the master ring and the scale is calibrated; i.e. if the master ring diameter is 4 microns smaller than the target value, the

scale is rotated so that the pointer shows -4 microns. The difference between the target value and the master ring inner diameter is determined by the measurement room personnel during the annual master ring calibration and is written on the master ring.

2. Master ring temperature measurement: the temperature of the master ring is measured by a digital thermometer. In order to do that the operator points the thermal sensor to the master ring, holding the sensor in one hand and the thermometer in another.
3. Washer temperature measurement: the same operation is repeated for the machined washer.
4. Measurement of the washer's inner diameter: the operator uses calibrated SUBITO to get the current deviation of the inner diameter from the target value.
5. Temperature comparison: the operator does the mental arithmetic to compare the temperature of the master ring with the temperature of the washer.
6. Estimation of the inner diameter value: the operator checks a table to get a heat compensation value. For each nominal diameter there is a separate table, which shows how many microns should be compensated for each integer degree of temperature difference between the washer and the master ring.

Having done these steps the operator is supposed to know what is the difference between the inner diameter of machined washer and the target value. If this estimated value falls outside the specification the washer is either reworked or scrapped. The process can be depicted as in Figure 4.1.

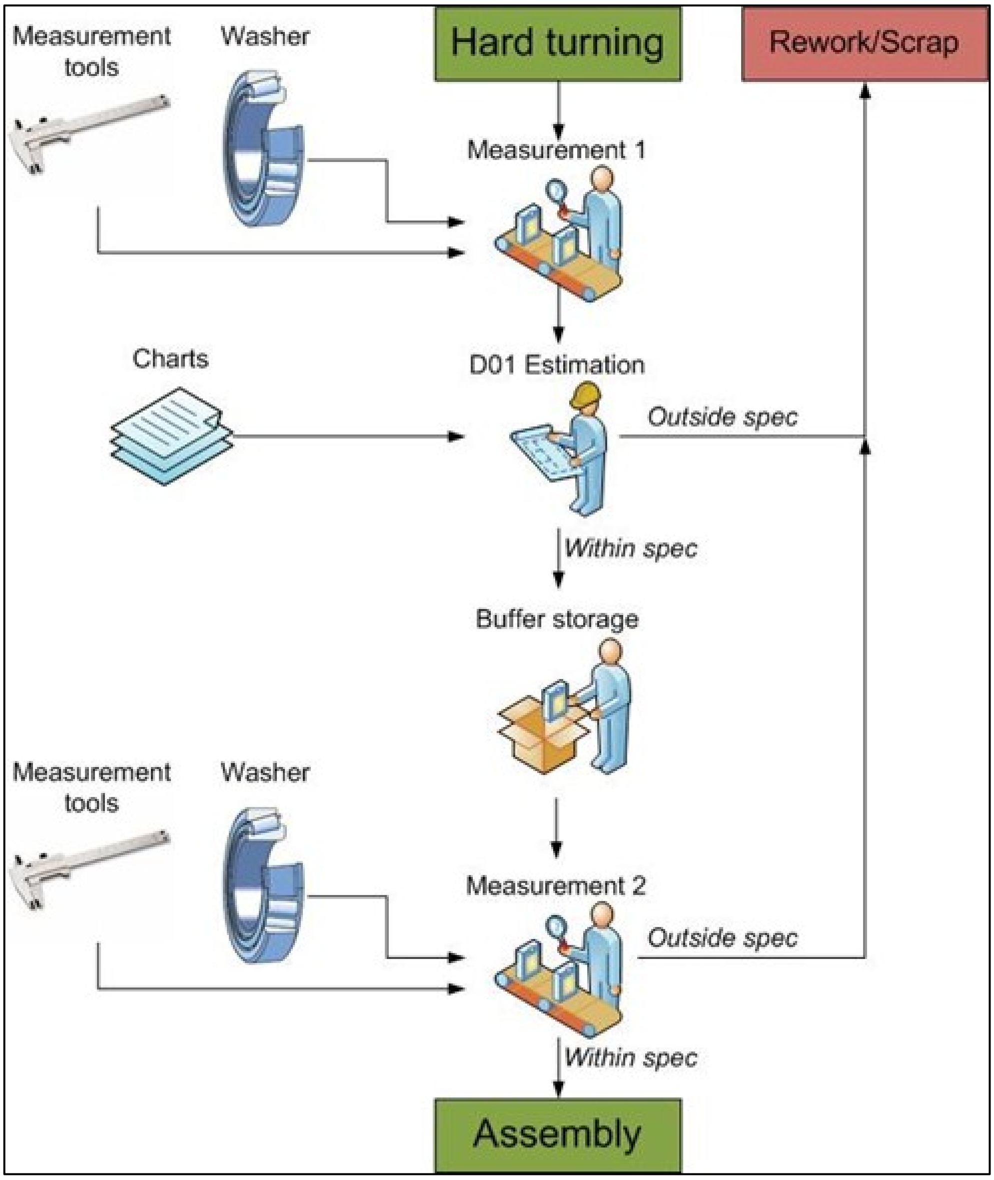


Figure 4.1: A process map for the measurement process.

Accepted washers are then displaced into a polishing machine, which does not affect the inner surface. After this operation washers are put onto a pallet and moved to the assembly station. Time interval that washers are dislocated at the assembly station before the final assembly operation is usually counted from several hours to several days. Right before the final assembly process all washers are inspected again, the procedure for inner diameter check is mostly similar to the first inspection, but the heat compensation is not counted as it is assumed, that temperature of the ring does not differ from the master ring temperature, as both pieces are dislocated in the same environment for a sufficient period of time. At this point a rather common situation is that some nonconforming washers are discovered, which means that either a wrong estimation of the inner diameter had been performed after the hard turning process, or the inner diameter is affected between the measurements by some unknown factors.

Detection of the washers that fall outside the specification at this point of time is destructive for the production process because the hard turning machine by that time is usually reset and tuned for hard turning washers of different diameter, and rework is difficult to perform. In order to perform an extra turning to achieve adherence to the specification, operators at the assembly station need to find all the washers in the batch that need to be reworked, and put them to the queue for hard turning. By-turn the operators of the hard turning machine need to finish the batch of washers of different diameter that they are currently working on, reset and tune the machine and then perform the extra turning of nonconforming washers. While these operations are performed the batch where nonconforming washers had been detected still cannot be considered to be finished.

Initial problem description

Many of the problems that were brought up at the beginning of the project were, in fact, not concerning the measurement process. Instead there was a lot of focus on the hard turning process that the measurements were controlling – quite natural, as there seemed to be many issues with the production cell, but not something that was included in this project. While there was no historical data covering these aspects, or anything else regarding the measurement process, it was also the general consensus that the measurements at the two measurement stations in the process got different results despite measuring the same thing with identical tools. The main problem, as seen by the involved people, was that it was unknown whether or not the tables used for the estimation of the thermal expansion (or rather, shrinkage due to a temperature decrease) were correct or not. So the main suspects for the measurement errors (or difference) were the tables, and the focus of the project team was initially driven by this hypothesis. Another factor that was included in the project focus was the measurement system in terms of tools used for diameter estimation.

Another problem in the measurement process is the necessity of double check of the inner diameter. It was pretty obvious for everyone that not only the measurement itself is a non-value adding activity, but also that performing exactly the same inspection twice in the process a pure waste. Elimination of at least one measurement was seen as required. The easiest way to do so was to change the procedures for measurements and leave the whole inspection to the assembly station skipping the first measurement inside the hard turning machine. However, this was not an option due to the reasons described in the previous section, as it could dramatically increase lead times due to the need of resetting and tuning the hard turning machine. Thus the project scope was set to the following structure:

- Discovering the route cause for measurement differences between two stations;
- Developing a new way of measurements, which would be able to guarantee 100% accuracy of diameter estimation at the first measurement station;
- Assuring that no difference in measurements would occur in case of double check;
- Eliminating the need for the second measurement.

The main gain in case of successful solving of the aforementioned requirements would be the reduction of non-value adding activities and thus the man-hours spent on them, reduction of lead time, reduction to zero of setup times in case of needed rework and a greater certainty in terms of products adherence to the specifications.

Additional benefits from the project were defined as a possibility to implement statistical control over the hard turning process, which would provide better understanding of the production process as well as ability to track the hard turning process capability.

SIPOC

The first step that was taken in order to build an understanding of the measurement process was a SIPOC. Several meetings were carried out with the goal to get a full picture of the process. As it is important to capture all aspects two SKF green belts with knowledge of the process were involved in this step: production manager Kostadin Kostovski and production technician Johan Welinder.

The SIPOC (Appendix 4.1-2) shows the outputs and inputs of the process, and what requirements the customers (or the process itself) have. Process boundaries were determined helping to delimit the project and focus on important process steps. Most outputs can be seen to have mostly internal customers, within the process itself as the customer isn't overly concerned with how measurements are done – only that the correct decisions about the products are made so that the delivered goods adhere to the specifications.

All the suppliers listed in the SIPOC table were chosen as a primary focus for the data collection and measurements. The measurement devices – the diameter gage, thermometer & the temperature charts – and their ability to provide good measurements or calculations are (unsurprisingly) crucial to the performance of the measurement process and needed to be checked for their ability to fulfill the process requirements.

P-Diagram

In order to classify the inputs to the measurement process as well as to define what the output is, there was created a P-Diagram presented in Figure 4.2.

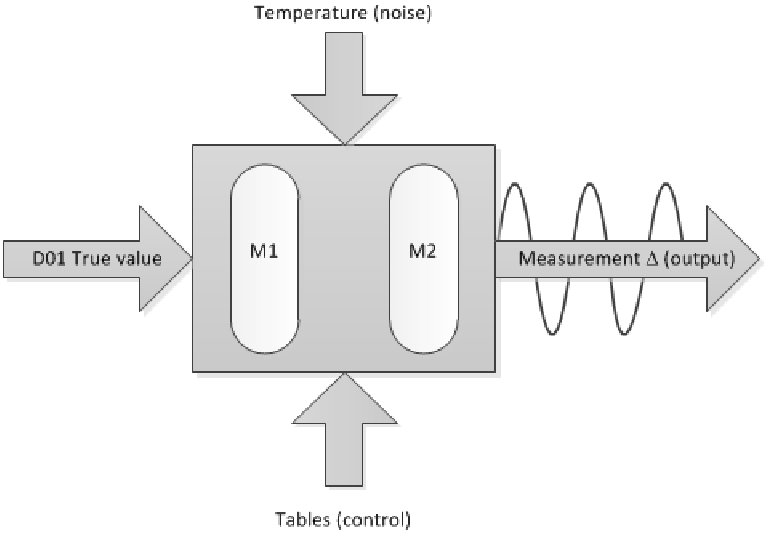


Figure 4.2: A P-Diagram for the measurement process.

The process box in Figure 4.2 consists of all the process steps shown in the process map, Figure 4.1. These steps for the sake of convenience were divided into two sub-processes: M1 and M2, which stand for the first and the second measurement respectively. While M1 involves temperature and diameter measurement as well as the heat compensation estimation, M2 stands only for a single diameter measurement at the assembly area.

In the current state there was a difference between two measurements of the same variable (inner diameter). This difference (also referred to as "measurement Δ" or "ΔD") was assigned to be the process output. As there was no historical data regarding the inner diameter measurements, the nature of ΔD distribution was unknown. This led to the necessity for collecting the data regarding the difference between two measurements.

A real value of the inner diameter was seen as a process input. However, it is believed that the true value is always unknown and unknowable. This statement is one of the cornerstones of any measurement process, as any measurement is just a comparison of one variable with a reference.

Temperature fluctuations were agreed upon being a noise factor, as they involve quite a big number of affecting agents, including environmental aspects, making it very difficult, if not impossible, to control. The general hypothesis about the temperature variation effect on the measurement process capability in terms of ΔD variation was: "whatever the temperature of the washer is, the process must be capable to predict the value of the inner diameter after the first measurement, and ΔD must be always equal to zero". In other words, the measurement process must be insensitive (robust) to any temperature variation.

The control factors for the process were defined as heat compensation tables used for the diameter estimation. Indeed, all numbers used for heat compensation were predefined at a certain level, depending on the washer dimensions. This numbers were then extracted from measured values, thus affecting the measurement process a lot.

However, one more factor was selected to be studied with the first priority – the measurement system in terms of used tools. The basic hypothesis explaining the necessity for tools testing is as follows: if the measurement system cannot provide reliable data there is no point to improve other parts of the process, until the measurement system capability is sufficient.

Tools used for measurements and heat compensation tables were prioritized to be looked at very carefully, as they had the biggest possibility to introduce a measurement error leading to the measurement difference occurrence. This prioritization has shaped the initial focus for the measurement phase.

4.2 Measure

As mentioned in the theory chapter, the measure phase is about identifying what inputs affect the outputs of the process and what their impact on the results are. In this project that was mainly done through experimentation and measurements, but also through observation and listening to operators, process & quality managers as well as experts.

Impressions of the process

To understand the process well enough to be able to judge it a lot of time was spent in the factory, combining observation with discussion and asking questions. It was all carried out in a considerably un-structured and un-standardized way in order to learn without applying any prejudice.

Our first impressions of the process was that it was surprisingly difficult to follow, something that at later stages of the measure phase caused slight problems with the more quantitative parts of the data collection. There were many different buffers and zones where the washers were being placed throughout their path from the hard turning to assembly.

As for the measurements that were carried out, it does indeed seem like that the exact same measurement of D01 was carried out two times, where the only thing that differs is the time and thereby the temperature of the washers. These measurement were being used for a go or no-go decision, but the actual values were never noted down or stored in any way. Because of this there were no historical data to analyze and a data collection series was later initiated.

The work area and the operators working there varied much in the level of apparent work being carried out. Sometime there seemed to be much fewer operators than at other times (ranging from 2 to at least 4), while the same amount of work was supposedly carried out. It also seems like the “bottle neck” for the flow through the entire LT5 channel is the hard turning process, and that each process step after that has a higher throughput.

Asking the operators what they thought about the results of the measurement process revealed that they believed that the operator skill, and understanding of how the hard turning works, was a factor that could affect the readings in some way.

Looking at and attempting to use the tools used in the process, the SUBITO and the thermometer, revealed that it was quite easy for someone inexperienced or simply out of focus to make relatively large errors.

Process mapping

While the SIPOC is a great tool for getting a quick first look at the process it was deemed necessary to take a closer look at the process, its outputs as well as all things affecting the performance. Especially the vital measurement station directly after the hard turning of the washers was of interest here and the later parts were subsequently excluded as it was assumed that neither storage nor polish of surfaces unrelated to the axle shaft had any effect on the inner diameter. In order to do this a process mapping technique was used.

The measurement part of the process was first broken down into five clearly visible steps: the calibration of the SUBITO diameter gage, the diameter measurement on the washer, the measurement of temperature on the master ring, the measurement of temperature on the washer and finally the estimation of the real value of the diameter at room temperature.

Any outputs for each process step were listed, followed by all inputs. See Appendix 4.2-1 for the full table/list of inputs and outputs.

Measurement System Study

One of the most important aspects of a measurement process is of course the tools and methods used. In the LT5 production channel two tools were used: the SUBITO diameter gage used to measure the inner diameter and a thermometer. Gage R&R studies were performed on the two types of tools.

Thermometer Gage R&R

The study was carried out using three operators (A, B and C), four different parts (1 – 4): two placed in the main factory building and two placed in a temperature controlled laboratory environment nearby. The experiments were carried out in a completely randomized order using the same thermometer for all measurements. Each operator-part combination was repeated three times, resulting in total of 36 experiments.

Appendix 4.2-2 contains the tables regarding this experiment.

The specification charts for the gage were also looked at, revealing an accuracy of ±0.5°C + 0.3% of the measurement value (Nordtec AB, 2011).

SUBITO Gage R&R

For the diameter gage two different tools were included in the study (tools 1 and 2). Three operators were used (A, B and C) and three different parts (1 – 3). Each tool-operator-part combination was repeated three times resulting in 54 experiments. Again the experiments were performed in a randomized order.

Appendix 4.2-3 contains the tables regarding this experiment.

Data collection

As no data was being collected (or more accurately, stored) at the measurement stations, it was seen as a necessity to start doing this in order to get a real understanding on how well the process was performing. One of the main reasons that this project was started was a perceived discrepancy between the measurement results at the two stations and therefore a data collection plan was initiated with the goal of capturing any mismatch in the measurements.

The collection plan consisted of a simple table at each of the workstations. At the first station, the rings would be marked with a number. The diameter of each washer was to be noted down with two replications, as well as the temperature of both the washer and the master ring, in the table. At the second measurement station operators were supposed to read the number of the washer, perform the measurements and write down the value of inner diameter in a line with the corresponding number.

After the first set of data was collected there were noticed some strange patterns like for example a ring rejected at the first measurement station appeared in the table from the second measurement station. Another issue was tremendous difference in diameter value between two replications of the same measurements. These problems could be explained by the lack of attention from operators as well as by complexity of the procedure leading to misunderstanding of the instructions. To avoid this type of errors there was initiated a new data collection with more mistake-proof solutions.

The same measurements were intended to be performed by the operators. This could not be considered as an extra work because only the standard measurements were needed and operators performed them on the day-to-day basis. Operators at the first measurement station were asked to mark all washers with numbers as well as with a line indicating where the measurement was to be taken. The diameter of each washer was to be noted down (this time with only one replication), as well as the temperature of both the washer and the master ring, in the table. At the second work station the same measurements were to be performed and noted down. However, lines in the table for the second station were not marked, and operators had to fill in the number of the ring which excluded a possibility to entangle the table lines. Diameter measurements were to be taken in the position indicated with the line which was exactly the same position as at the first station.

The instructions for each work station can be viewed in appendixes 4.2-4a, and the data collected in appendixes 4.2-4b.

Experimental exploration of thermal expansion in washers

The steel used in the bearings produced by LT5 has a thermal expansion coefficient (α) of $11.5\mu m \cdot m^{-1} \cdot K^{-1}$(Carlsson, 2011). However, as the washers are measured before and after cooling down in the process and the results appear to be unpredictable an experiment in a more controlled environment was carried out in order to experimentally secure that the washers cool down in accordance to what is expected.

Two washers were transported to a laboratory where one was kept at room temperature (22.5°C – 22.8°C) for reference while the other was heated to approximately 33°C. The heated component was kept in the oven for an extended time in order to assure an even spread of the heat in the material and then taken out of the oven for the experiment itself.

The procedure for the following experiment was simple: firstly, the temperature of the cooler ring was measured and subsequently the SUBITO diameter gauge zeroed at a predetermined and marked point. Then, the temperature of the heated ring was measured and lastly the diameter of this ring. This measurement was also carried out at the same point every time. The results were noted down in a table. The procedure was repeated every 5 minutes for 120 minutes (25 measurements). The thermometer used was a Testo 922, which was the thermometer used in the LT5 channel.

The experiment was performed once again at a later date, this time slowly cooling down the ring previously heated by placing it in a colder environment. This time the ring was measured 15 consecutive times following the same procedure as in the previous experiment. This time a different thermometer was used; the Testo 735.

The two washers were also measured at the same temperature. This measurement revealed that the inner diameter of the heated up ring was, at equal temperatures, approximately 4µm smaller than that of the unheated ring.

The results can be seen in Appendix 4.2-5.

Potential Failure Mode and Effect Analysis (PFMEA)

At this point it became clear that it would be necessary to use another method to further understand the possible reasons for the shortcomings of the process. The decision was based on the fact that the performed actions, MSA and the data collection mainly, seemed to give rather conflicting results. PFMEA was selected as an appropriate tool for this task.

The process steps from the Process Mapping session were used to build the PFMEA, with the exception that the two temperature measurement (master ring and work piece) were merged into one step. Subsequently, all potential failure modes for each step were listed, and similarly all potential causes and effects for each failure mode were written down. See attachment 4.2-6 for the full list, and PFMEA table. Subsequently all failures were given a severity value (SEV), an occurrence number (OCC) and a detectability value (DET). For each of these categories there were four available levels (1, 4, 7, and 10: higher levels are worse), see table 4.1.

Table 4.1: The different levels available for each category in the PFMEA, with brief descriptions.

Severity (SEV)		Occurrence (OCC)		Detectability (DET)	
10	Process breakdown	**10**	Very often, 80% of the times	**10**	Impossible to detect
7		**7**	50%	**7**	Detected by chance
4		**4**	20%	**4**	System exists
1	1 micron error	**1**	Almost never	**1**	Hard to miss

As soon as all failure modes had SEV, OCC and DET values assigned, the calculation of Risk Priority Numbers (RPN) commenced. This was done by multiplying the three numbers with each other ($RPN = SEV \times OCC \times DET$). For the highest RPN-values (all lines with an RPN over 100), a quick brainstorming session generated potential improvements that would reduce the numbers in some way, and new SEV, OCC and DET values were assigned to the improved solutions. RPN values were calculated for these numbers as well.

4.3 Analyze

This chapter contains the analysis of the broad insights from the Define phase and the collected data from the Measure phase by the use of appropriate methods (Chapter 3) and theory (Chapter 2).

Judgments on the initial process

Looking back to our first impressions of the process, it is already clear that it is not perfect. Many of the “seven wastes” of lean thinking seems to be present: waiting (for the hard turning machine to finish the washers), transportation (between the several zones after the washers are completed and until they reach assembly) and defects (defects in the measurement values, the measurement of D01 is carried out in the exact same way twice: the only reason that this can be seen as necessary is that the measurements give so “random” results).

The fact that the production process has two possible outputs, products within specification and products outside specification, means that there are several possible scenarios concerning the result of the measurement process. See table 4.2 for a list of possible scenarios. For a washer within specification every measurement can be seen as some sort of waste – why measure a good product twice (waste)? The other option here is that either measurement station gives a false alarm that causes unnecessary scrap or rework. The wasteful scenarios for washers outside specification are more severe if the first station wrongly accepts the detail. In the best case scenario the second station catches the faulty washer (this can cause unnecessary setup time as the hard turning machine may well have been setup for a different type of washer) or worse let the product out to the final customer.

Table 4.2: Different scenarios for the outcome of the measurement process and the different types of waste connected to each.

True value	Measurement 1	Measurement 2	Result
Within specification	Accepted	Accepted	Waste (double)
Within specification	Accepted	Rejected	Waste (false)
Within specification	Rejected	-	Waste (false)
Outside specification	Rejected	-	Good decision
Outside specification	Accepted	Rejected	Waste (late alarm)
Outside specification	Accepted	Accepted	Waste (wrong!)

When looking at the outputs of the measurement process another waste is obvious: the data from the measurements are only used for a go or no-go type decision. This completely disallows any structured efforts to improving either the hard turning process capabilities or the measurement process without unnecessary amounts of extra work in the form of data collection.

From what the operators say, it seems as the measurement with the SUBITO is very subject to who is using the tool. Our own experiences of the tools show a similar picture.

Measurement System Analysis

An early criticism of the performed gage R&R experiments was that all three involved operators had, according to themselves, very similar experience in using the tools. Also, results may have been biased due to the fact that all operators were within hearing range of the reporting of results and/or knowing which piece they themselves were measuring. This could potentially cause them to subconsciously alter their readings to the results they expect to find. As all three operators claim to be very interested in finding out the truth about the process we assume that this type of bias had a very limited effect.

Looking at the results alone however (see Table 4.3 / Appendix 4.2-2 & 4.2-3) reveals that all three tools (thermometer, both diameter gages) perform very well with total Gage R&R values of well below 10.

Table 4.3: Gage R&R results for the different measurement tools.

	Thermometer	SUBITO 1	SUBITO 2
	% Contribution	% Contribution	% Contribution
Total Gage R&R	7.63	6.01	4.99
Repeatability	6.91	2.81	3.01
Reproducibility	0.72	3.19	1.99
Part-to-part	92.37	93.99	95.01

This would mean that the tools are well suited for the task at least in the hands of operators with similar and high skill levels and used in a controlled environment.

Analysis of data collection

The results of the data collection gives a completely different picture: the calculations performed directly after the hard turning process lead to estimations of the actual inner diameter that are not at all accurate when measured again just before the assembly, see Figure 4.3 and Appendix 4.2-4b for the results. As can be seen very few of the data points for the estimation correspond well to the measured values at the assembly.

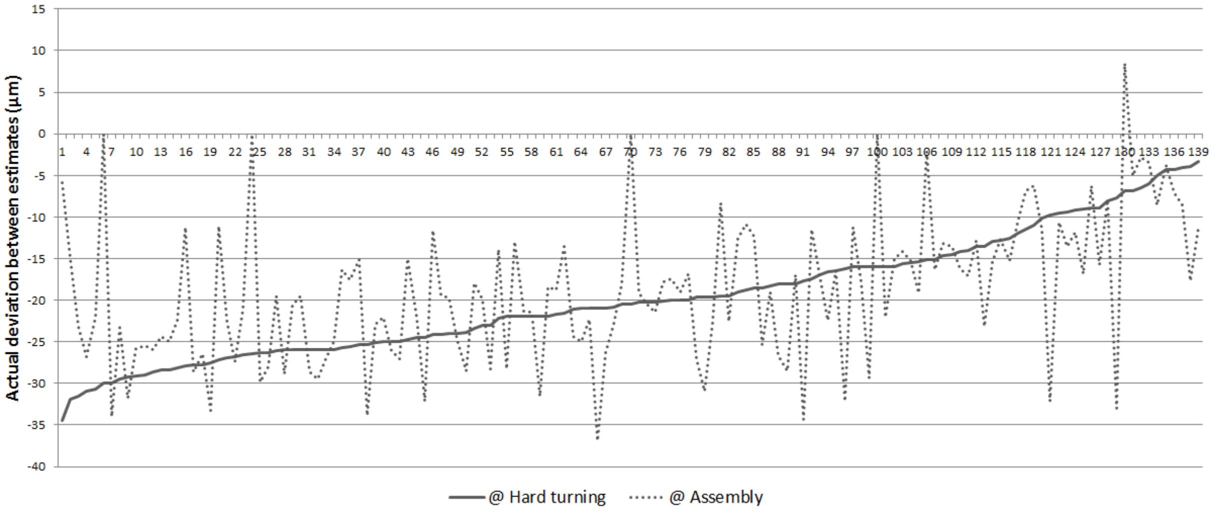


Figure 4.3: Diameter estimations at hard turning and assembly, sorted by value at hard turning.

The error (meaning the difference between the estimation of the diameter at hard turning and at assembly) ranges from -30µm to +25µm, with a mean close to 0µm. The data points seem to be normally distributed with a standard deviation of ~8.31. For a visualization of the error, see Figure 4.4 and Figure 4.5.

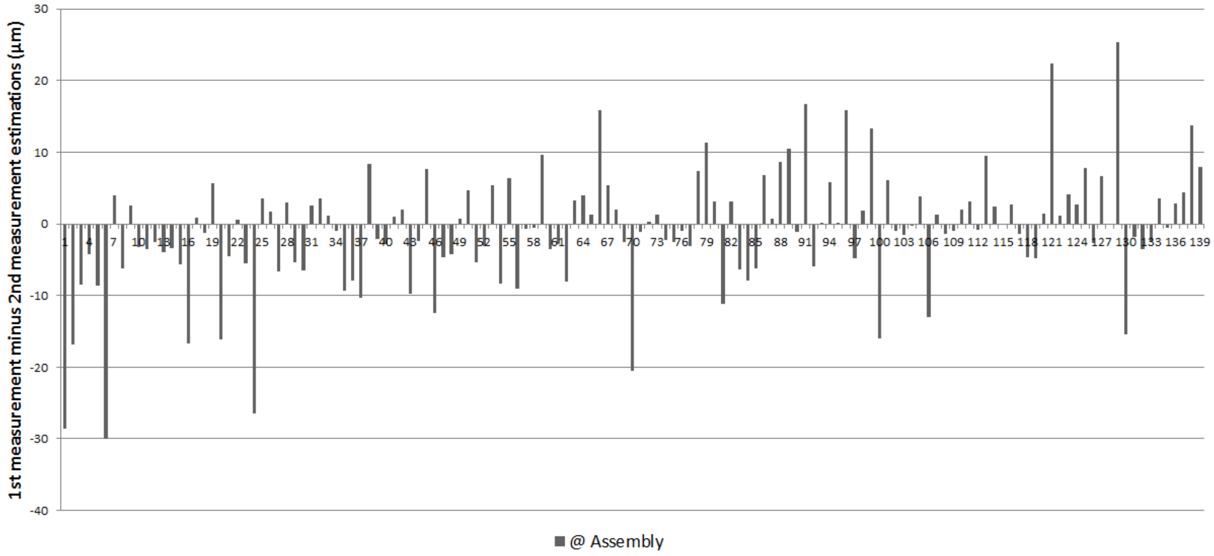
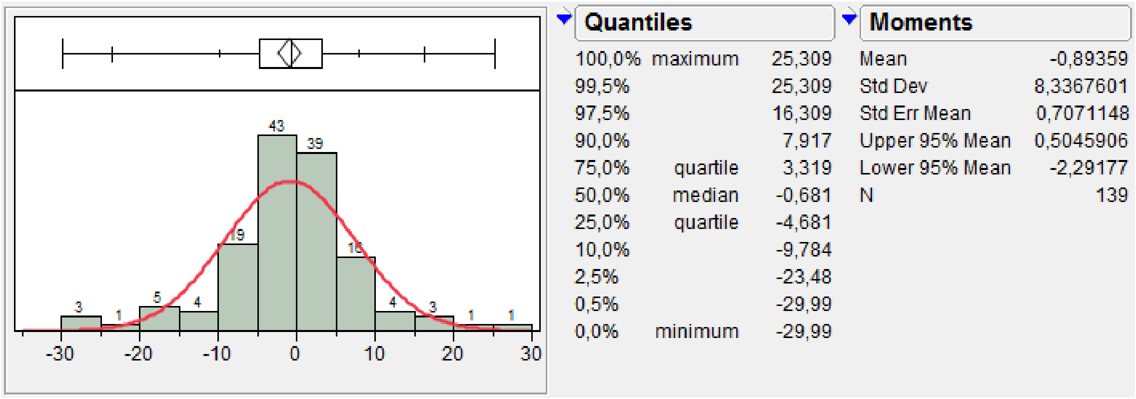


Figure 4.4: Difference (error) between measurements at hard turning and assembly, sorted by diameter value at hard turning.

There seems to be a clear correlation between the measurements made directly after the hard turning and those done at assembly, which is to be expected, and positive. What is not equally positive is the frequency and magnitude of the errors. The error range in the data collection set is equal to approximately two times the tolerance span (from ±0µm to -30µm for washers of this type) and more close to one third of the washers measured should be expected to be more than 8.31µm larger or smaller. Even if a washer is measured to be exactly in the middle of the tolerance range (-15µm) it is impossible to be more than 95% certain that it actually is within specifications.



Quantiles

100,0%	maximum	25,309
99,5%		25,309
97,5%		16,309
90,0%		7,917
75,0%	quartile	3,319
50,0%	median	-0,681
25,0%	quartile	-4,681
10,0%		-9,784
2,5%		-23,48
0,5%		-29,99
0,0%	minimum	-29,99

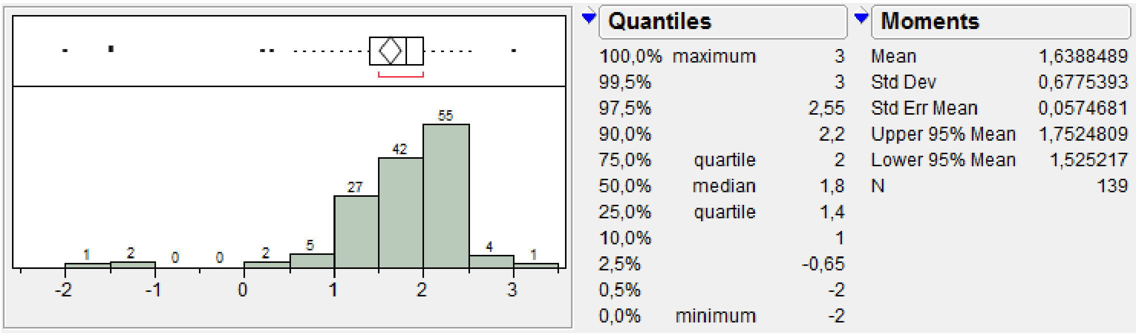
Moments

Mean	-0,89359
Std Dev	8,3367601
Std Err Mean	0,7071148
Upper 95% Mean	0,5045906
Lower 95% Mean	-2,29177
N	139

Figure 4.5: Distribution of the error with counts.

The analysis of the data collection confirms the suspicion that the two measurement stations get very different results, but it also reveals that there is no pattern existing.

However, one observation is worth mentioning. The vast majority of all washers after the hard turning fall into a relatively narrow interval of temperature difference between them and the master ring, see figure 4.6.



Quantiles

100,0%	maximum	3
99,5%		3
97,5%		2,55
90,0%		2,2
75,0%	quartile	2
50,0%	median	1,8
25,0%	quartile	1,4
10,0%		1
2,5%		-0,65
0,5%		-2
0,0%	minimum	-2

Moments

Mean	1,6388489
Std Dev	0,6775393
Std Err Mean	0,0574681
Upper 95% Mean	1,7524809
Lower 95% Mean	1,525217
N	139

Figure 4.6: Distribution of the temperature difference at the hard turning with counts.

There are some outliers included in the figure, but the overall impression is that the most important temperature difference interval is 1 to 3 degrees, as the biggest amount of estimations made after the hard turning are made in these limits.

PFMEA analysis

The PFMEA revealed that there were many failure modes with very high Risk Priority Numbers (RPN). Many of these were already known quite well, such as if the temperature correction tables were incorrect it would severely harm the process. What was perhaps more interesting is that the recommended actions that were quickly generated during the PFMEA session pointed towards a few major improvements, despite the wide variety of failure modes. The main improvements seemed to circle around three things: firstly, a change in diameter measurement tooling to a setup that was less sensitive to errors in use (due to in-attentiveness or lack of experience), the second a change in thermometer to one that had a greater accuracy and did not require so much time and patience from the operators in order to get good readings, and finally an increase in automation to make sure that the calculations necessary in the process were performed without errors.

Analysis of thermal expansion experiment

Before proceeding with the analysis of the thermal expansion experiment, some criticisms of said experiment is necessary. Firstly, the tools used are now known to be less than perfect for the task: the thermometer due to the low accuracy (± (0.5°C+0.3% of the measured value)), and the SUBITO gage for being difficult to use for anyone except the most experienced. Secondly, the experiment was only done once, without any repetition to secure the data. The second data set was performed in a less controlled environment and involved transportation of the diameter gage between the two areas with different temperature. This could have affected the gage itself.

Now, looking into the data revealed by the experiment we can plot the calculated value of the heated ring and the measured value of the heated ring over the temperature delta between the heated and the unheated ring. This gives us a good view of the data, as can be seen in Figure 4.7.

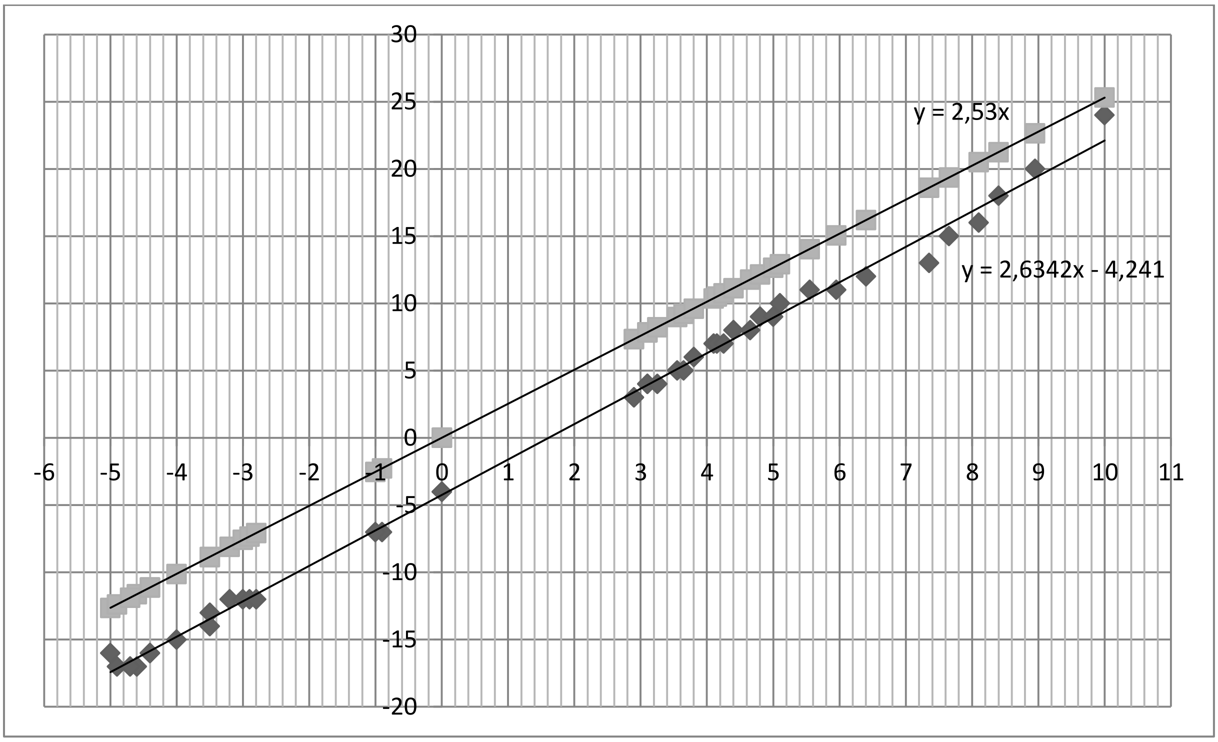


Figure 4.7: The results from the temperature coefficient experiment. The dots making up the upper line (y = 2.53x) are the calculated values for each temperature delta. The lower line (y = 2.6342x - 4.241) represents the actual measured values.

Adjusting the values of the measurements to form a trend line that can be extrapolated backwards to a point with zero temperature difference gives us a formula for each data series: y_1 = 2.53x for the calculated, or expected values, and y_2 = 2.6342x – 4.241 for the experimentally determined values.

For y_1, this formula can be back-tracked to the formula for thermal expansion:

$$L_2 - L_1 = \alpha L_1 (T_2 - T_1)$$

Assuming an alpha of 11.5 and L1 to be close to 0.22m:

$$L_2 - L_1 = 11.5 \times 0.22(T_2 - T_1) = 2.53\Delta T$$

In order to prove that the rings follow this theoretical model when heating up and cooling down we should see the same behavior in the experimental values, $y_1 = y_2$. As the two rings measured at the same temperature differ ~4µm (the never-heated ring being 4µm larger), we can see that this is in fact approximately true. The alpha values, while not matching perfectly, are relatively close:

$$2.6342 = 0.22 \times \alpha \rightarrow \alpha = 11.9736$$

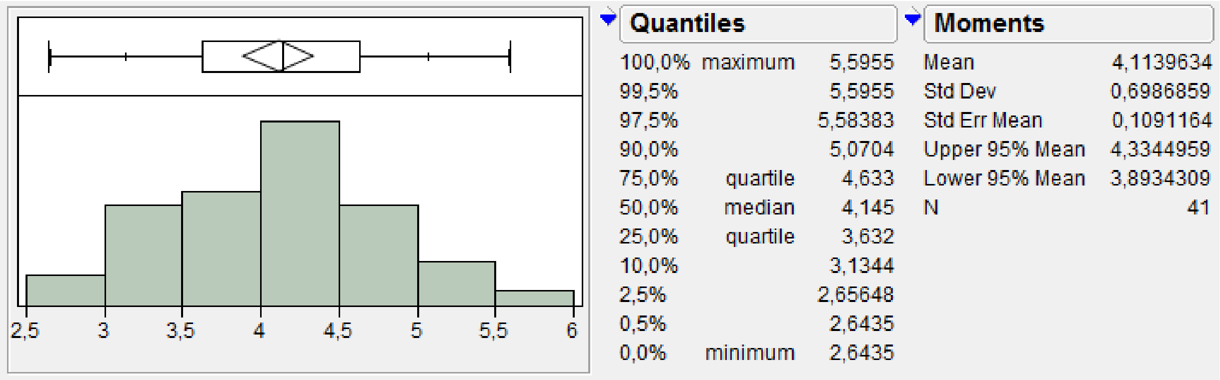
This discrepancy can be explained by the inaccuracy of the thermometer used in the first experiment as well as the relative inexperience of the operator performing the measurements.

Looking at only the values from the second data set that was collected using the better thermometer (Testo 735) we see better values:

$$y = 2.5406 - 4.5905$$

This would represent an alpha value of 11.545µm · m^{-1}· K^{-1}. This proves that the material used in the washers likely has the expected coefficient for thermal expansion, and that the rings themselves behave in a way that can be easily predicted.

To secure that data gathered during the experiment is trustworthy enough to support any conclusions we can look at the histogram of ΔD, which is a calculated value of the difference between the reference ring diameter and heat compensated diameter of the temperature affected ring. We know that with zero temperature difference diameters of those rings differ for ~4µm, so the expected mean value for ΔD should be close to 4µm. The distribution analysis of ΔD is presented in Figure 4.8.



Quantiles

100,0%	maximum	5,5955
99,5%		5,5955
97,5%		5,58383
90,0%		5,0704
75,0%	quartile	4,633
50,0%	median	4,145
25,0%	quartile	3,632
10,0%		3,1344
2,5%		2,65648
0,5%		2,6435
0,0%	minimum	2,6435

Moments

Mean	4,1139634
Std Dev	0,6986859
Std Err Mean	0,1091164
Upper 95% Mean	4,3344959
Lower 95% Mean	3,8934309
N	41

Figure 4.8: Analysis of ΔD distribution.

As can be seen from the histogram, ΔD is normally distributed around the mean value of 4.11µm, which is very close to the expected value; 80% of calculations fall inside ±1µm interval; and all the calculations do not outstand from the mean value for more than 1.5µm.

To check if there is any correlation between the temperature difference and the amount of error incorporated in the diameter estimation we can look at the bivariate fit of ΔD by ΔT presented in Figure 4.9.

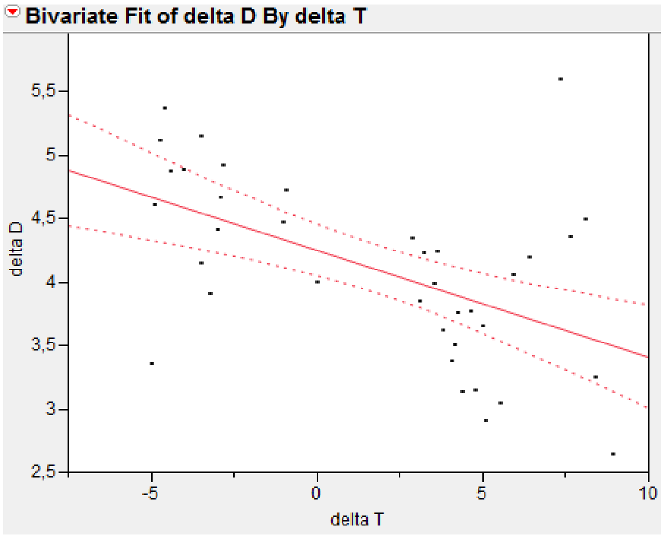


Figure 4.9: Bivariate of ΔD by ΔT.

As can be seen from the figure, the fit line is slightly inclined. The linear fit is described by the following formula:

$$\Delta D = 4{,}2538093 - 0{,}08401 * \Delta T$$

This might mean a presence of possible correlation between the temperature difference and the amount of error incorporated in the diameter estimation. However, because the data is made up of two different sets where not all parameters were the same (a different thermometer was used, and the experiments were carried out at a different location) we cannot yet draw that conclusion. We need to look at the data sets separately, see Figure 4.10.

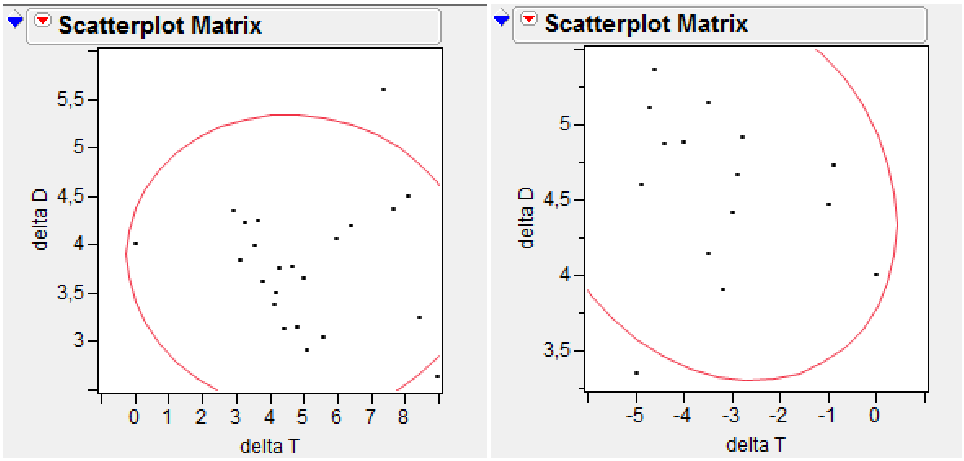


Figure 4.10: Separate bivariate fit of ΔD by ΔT for each experimental setting.

As we do not possess a lot of dots in each subset and dots seem to be distributed quite randomly, it is pretty obvious, that the regression line will have a huge error incorporated in it. Instead of approximating a linear regression line for each subset we build a density ellipse with a 0.95 coverage. This means that 95% of all dots lie inside the ellipse. The base line of these ellipses is that the more stretched they are along one of diagonals the more likely is the presence of correlation.

If we look at density ellipses of each experimental sub-set it seems that no correlation is present between the variables. Absence of correlation indicates that the different thermometer or setting would be what had influenced the fit model of the experiment.

This solidifies the previous statement that the formulas that created the temperature compensation charts are correct.

P-diagram

Looking back at the P-diagram presented in the Define phase (Chapter 4.1) it is now clear that our view on the process at that time, while proving to be useful in finding the important factors impacting the measurement process performance, was somewhat flawed. See Figure 4.11 for a new version of the P-diagram.

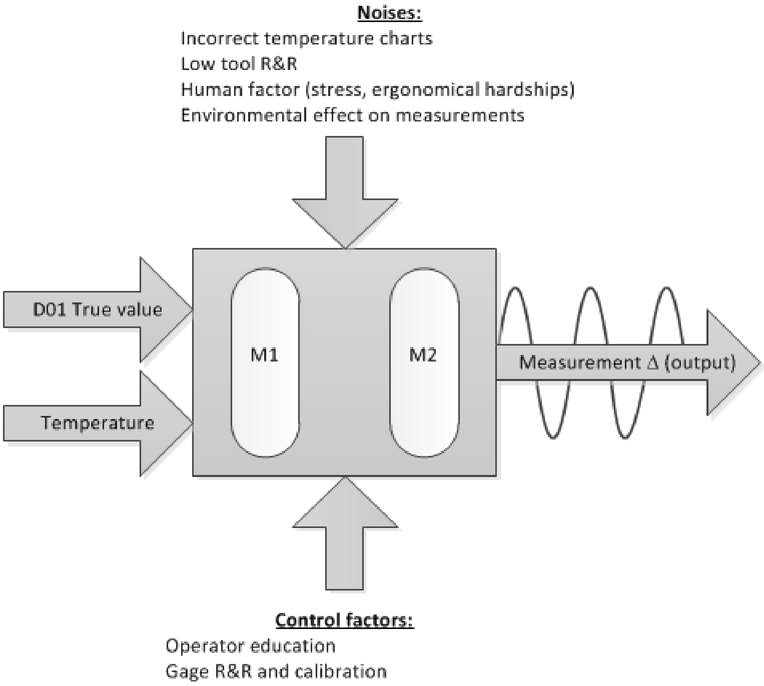


Figure 4.11: A new P-diagram describing the measurement process.

As can be seen in the diagram it is more accurate, for the measurement process to consider both the true diameter value of the washer and the temperature difference between the product and the master ring as inputs. There are several new noise factors that could be affecting the result of the process: incorrect temperature charts, low tool R&R, the human factor induced by stress or poor ergonomics in the design of the measurements and environmental effects on the measurements (such as the washer being covered in coolant or metal shavings). Some of these have been confirmed to be very low or non-existent: the temperature charts are quite accurate and the tools perform well in a controlled environment. The human factor, as well as tool issues, already has control factors in place: operator education and rigorous calibration routines.

Putting the pieces together

The different data collection efforts can be seen as several vantage points overlooking the same issue, and combining them gives a better picture of the problem. From the MSA it can be clearly seen that the SUBITO tools, when used in a controlled environment by skillful operators that are very interested in receiving reliable results, are very good. But when the same method is used in production the data collection efforts show that the results are very unpredictable indicating that either the theoretical model used for heat compensation is wrong, that something happens to the work pieces between the measurement stations, or that the tool just isn't as easy to use in a real environment. Between the two measurements there is only one activity that could affect the work piece: a polishing operation. This operation does not directly affect the inner diameter, as the surfaces inside the washer are not polished. The operation can however be assumed to affect the temperature of the work piece.

By performing a controlled experiment looking at this heat compensation it can be determined that the model is correct. This means that even if the washer is heated again in the polishing operation, the inner diameter can still easily be estimated using the coefficient of thermal expansion. This leaves only one source of the variation in the collected data: that the methods or tools that are used do not function as well in reality as they do in a secure experimental setup.

In the PFMEA a few lines stand out, both because their "Risk priority numbers" are very high, but also because the potential improvements of these numbers are equally large. These lines point to three major possibilities for improvement: firstly, a new tool that is less susceptible to human errors due to inexperience, fatigue or general lack of attention should be sought. If such a tool can be found, it would reduce the RPN by one third. Similarly, the introduction of a new thermometer that is more accurate and less affected by the patience of the operator (who has to hold the thermometer against the washer/master ring for an extended amount of time) and a more protected contact sensor would be very beneficial. The third big improvement that, according to the PFMEA, should be sought is an increase in the automation of the calculations in the process – this would lessen the risk of mistakes in the heat compensation step.

4.4 Improve

This chapter contains the improvements either suggested for implementation, or already implemented changes as well as the reasoning behind these actions. It is to a great extent based on the analysis (Chapter 4.3).

Improvement thoughts

Judging from the analysis, there were a few things that needed improvement, as well as some things that can be excluded from the improvement list. The formulas used in the temperature correction tables for example did not need any major changes. On the other hand it seemed that an automation of the calculations involving these tables would be beneficial.

Firstly, the thermometer was seen as too inaccurate and too time consuming to use properly.

According to the conclusions drawn in the analysis chapter it was also considered to be a good idea to look into replacing the SUBITO for diameter measurement, as it seemed to be quite easy for the operators to get very varied results in the measurement, mainly depending on who was performing the measurements.

Finally, the last suggestion was to add more automation in general for the calculations and storage of the measurement data. Preferably through a system that receives readings directly from the measurement equipment as to not add any new tasks for the operators.

Temperature measurement improvements

Through the measurements and analysis thereof three major flaws in the thermometer that was in use in the measurement process were detected: a relatively low accuracy (±0.5°C), a requirement on the operators to be very patient and careful during the measurement and the necessity to perform the calculation of the temperature difference.

A new tool would be required to perform better in all these three aspects. Another production channel within the large bearings factory had previously discovered the same problems in their measurements (unconfirmed, from interviews) and implemented a new thermometer, the Testo 735 with magnetically attached probes. This thermometer has an accuracy of ±0.2°C, which can be seen as much better. The probes are attached to the washer by the use of a magnetic tip cover that allows the operator to focus on other things while at the same time ensuring a good connection with the material. The tip cover also protects the sensors in a better way. It is also possible to by attaching two probes automatically calculate the temperature difference between the master ring and the work piece.

The decision was made to implement this type of thermometer.

Diameter measurement improvements

As it was surmised that the tool for measuring the diameter was, in real world application, difficult to use and sensitive to variations in this use it was seen as necessary to evaluate if a change of this tool would provide better results. At SKF several different tools that can potentially be used for this purpose were used: the SUBITO, HMD, internal micrometer sticks, UD machines and fixed size gauges(Johansson, 2011). A new tool, currently under development, called the “EasyMetric” was also included in the considerations. It was decided to use a Pugh decision matrix to evaluate the different options, as it would not be possible to test all the options in the measurement process.

A set of characteristics that were deemed to be important for the application was developed in cooperation with an expert on measurement equipment (Johansson, 2011). Each characteristic was given a “weight” value between 1 and 5 showing its importance in the decision.The following properties were identified:

Price – The price of the equipment is a crucial parameter, and naturally a low price is preferable. The price considers mainly investment costs for the measurement equipment itself but also for any necessary paraphernalia. This category was given the highest weight, 5.

Calibration – The calibration indicates the time and resources needed in order to calibrate the equipment. This category was given a weight of 2, as it is not something that generally affects the performance of the measurement process itself.

Ease of use – The ease of use, or how difficult it is to err in the usage of the equipment, is a key parameter for the equipment as it has been shown earlier in this report that variation in use is perhaps the largest source of error. It was given the highest priority, 5.

Ergonomics – Ergonomics is another important factor, given the weight 5. Bad ergonomics can cause serious injury and be a serious problem for the company. Included in this category is the amount of static holding of the equipment and the weight of the equipment.

Temperature sensitivity – Many tools are adversely affected by temperature fluctuations coming from for example holding the equipment in the sensitive areas. Small temperature fluctuations in the tooling can lead to large errors in the measurements. The weight equals 4.

Measurement performance – Naturally, the performance of the equipment in diameter measurement is important. All the tools included in the study are, however, relatively accurate and the weight is thusly given as a 4.

Ability to measure both inside- and outside diameters – The inner diameter is not the only critical dimension, and even though this project is focused on solving the problems in measuring that dimension the flexibility of the tools is something that should be considered. This characteristic is given a 1 in weight.

Ability to measure ovality – The inner diameter can vary depending on where inside the ring it is measured, as the shape of the bore may in some cases be slightly oval. There are limits to how oval the rings can be, and the ability to easily measure/calculate this is therefore of some importance (weight 2).

Each tool was subsequently assessed on each characteristic and given a value from 0 to 4, where 0 represents a complete inability to fulfill the criteria and a 4 represents a complete fulfillment. One option, the UD machine, was excluded from the discussion as it would require the washers to be removed from the hard turning machine. This was seen as a requirement as the ring is retrieved from within the machine by means of a robot, and changing this would require major alterations to the logistics of the production process (something that is not included in the scope of this project). For the resulting Pugh matrix, see Table 4.4.

Table 4.4: The Pugh decision matrix for diameter measurement tools.

		SUBITO		**HMD**		**EasyMetric**		**Int. microm.**		**Fixed gauge**	
	W	**V**	**Σ**	**V**	**Σ**	**V**	**Σ**	**V**	**Σ**	**V**	**Σ**
Price	5	4	20	2	10	3	15	0	0	0	0
Calibration	2	3	6	2	4	2	4	3	6	2	4
Ease of use	5	1	5	4	20	3	15	1	5	3	15
Ergonomics	5	2	10	3	15	3	15	2	10	1	5
Temp. sens.	4	0	0	2	8	4	16	0	0	2	8
M. perform.	3	2	6	3	9	4	12	2	6	3	9
Outside Ø	1	0	0	0	0	4	4	0	0	0	0
Ovality	2	1	2	1	2	4	8	1	2	4	8
Score			**49**		**68**		**89**		**29**		**49**

Based on the numbers from the Pugh matrix, the EasyMetric tool was considered to be the most promising solution. As can also be seen in the matrix, this tool performs well across the board and has no obvious weaknesses in any characteristics. However, as the matrix is a highly subjective tool it was seen as necessary to test the device in a real setting in order to verify the results.

Experimental verification of new tool usability

A prototype test run was performed with the EasyMetric tool. While this test run was not extensive enough to provide any statistical data the experience confirmed many of the assumptions made building the Pugh matrix.

It seemed to be very easy to use and appeared quite light weighted compared to the SUBITO especially considering that unlike that tool there was no requirement to hold the device fixed at one height during the measurement; instead the equipment was able to rest on top of the washer to be measured ensuring less stress on the arms and neck of the operator. Because of the carbon based material in the EasyMetric device the operator can also hold the tool anywhere without considering heat transfer from the hands into the tool. From the brief experiment the measurement performance appeared to be very good and the ability to measure the washer diameter “all the way around” the ring makes sure that any flaws are caught and that ovality can be measured with ease.

It is however important to remember that the tool is still in a prototype stage, and that before implementation can be realized some additional testing and adjustments to the situation in the LT5 channel should be done.

An automated system

Another stage of the suggested improvements was the implementation of a more automated system for calculations and generation of control charts. As this is highly dependent on the data outputted from the measurement equipment it has not yet started.

Elimination of the second measurement station

As it was mentioned before, all the measurements performed at the assembly area are just a repetition of measurements at the hard turning machine and thus are a wasteful activity. We suggest elimination of the second measurement station in the future. However, this improvement suggestion is fully based on the assumption that the new measurement system will be capable to provide 100% reliable measurements right at the hard turning machine; so this should only be done after extended testing and implementation of control system which will be described in the control section.

4.5 Control

This section presents a suggested plan for future monitoring and evaluating of proposed solution for its ability to fulfill set requirements. Another suggestion covered in this section is implementation of control system for hard turning and measurement processes through collection and analysis of available measurement information.

Initial system assessment

In order to control that suggested solution will be capable to provide precise and reliable information about the bore diameter of washers we suggest a set of activities. First of all, new tools should be evaluated through a new Gage R&R study to make sure that tools are capable to perform well in terms of repeatability and reproducibility.

To make certain that the system does not only possess required capabilities in theory but also works in a real environment of the factory and can provide reliable measurement information we suggest to perform a pilot test. Design of this test should not be overcomplicated, in contrast it should be kept as simple as possible in order to be easily replicable. We suggest a following design for a pilot test:

- Rings are measured with new tools inside the hard turning machine and marked with a number;
- Data about temperature difference and the ring’s diameter is typed into a simple table;
- Calculation of the heat compensation is done automatically by simple multiplication of the ring’s nominal diameter, thermal expansion coefficient and temperature difference;
- Estimation of the ring’s diameter is also performed automatically by adding the heat compensation value to its measured diameter;
- This iteration should be repeated for a sufficient number of washers, we suggest at least the number of 20-30 rings measured during one day;
- All information obtained during the test should be stored, including rings’ numbers, ΔT, heat compensation values, measured diameter values and estimated diameter values.
- Having done that, the batch of measured rings should be stored in the same environment with the master ring for a sufficient amount of time, like overnight, to even the temperature;
- Then rings should be measured again. At this step ΔT should be close to 0, but this, however, should be measured and stored anyways;
- Results of the second measurement should be typed down and then compared with the estimated diameter values.

This simple test will allow evaluation of the amount of error incorporated into measurement and estimation process. This data can be later plotted and analyzed by experts to conclude if the new system can perform as it is required. Even though we cannot predict the exact values that the new system will generate, we can expect the measurement error to be normally distributed with a mean value equal or close to 0 and a standard deviation (σ_{new}) much smaller than 8.34μm which is a current value of measurement error standard deviation. The new system can be considered to be very good if $\sigma_{new} \leq 1\mu m$, because in that case ΔD of 95.45% of all washers (2σ) will not exceed 2μm, which is a pretty fair level of needed precision. However, a judgment about the new system capability should not be made based solely on 20-30 measurement. The pilot test can provide only a hint about the real system capability, and if a concrete judgment is needed we suggest significant increasing of the amount of tested rings. Still, if the pilot test will show good results the system can be implemented while an extended knowledge about its real performance can be obtained and monitored through implementation of control system based on sampling and control charts. A suggested control system will be described in the following section.

Control system

There are two main areas of knowledge that can be obtained from control system application, these are:

- Knowledge about Hard Turning process capability;
- Knowledge about measurement system performance.

Simply gathering the information about the bore diameter and plotting it in a control chart can provide extended historical data for future projects in the field of analysis of the Hard Turning process performance. As it is now the new hard turning machine does not provide a stable process resulting in quite a big variation of bore diameter, thus 100% of produced washers are inspected. This information can easily be stored for future needs.

When it comes to evaluation of the measurement process performance, some adjustments are needed. Simple control charts can be used to generate alarms when the bore diameter falls outside the control limits or when there is a trend towards upper or lower control limits. Another suggestion is to set a control procedure which would consist of several steps. At the first measurement station samples of washers should be selected. Washers from a sample should be measured as usually then marked with numbers. When these washers arrive to the assembly area they should be measured again. Information about the bore diameter obtained through the second measurement should be compared with the information from the first measurement station. If the difference between two measurements (measurement error) is relatively small over a sufficient period of time, sample sizes and testing frequency can be gradually reduced. However, it is quite clear that the measurement error will still appear to a smaller or larger extent. Information about the measurement error should also be stored and analyzed providing a knowledge base about the systems performance that can expand and extend over time. Control chart for the measurement error could be used to generate alarms when the error becomes too big or when a trend towards bigger errors can be detected. This kind of alarms can inform the personnel that there are some sources of variation in the measurement process.

Having the information about the measurement errors, it is possible to calculate an average error for several previous samples. This data can be used as a feedback to the first measurement station, where it can be incorporated with the measurement process. In this case if the bore diameter of inspected washer lays inside the control limits there is no alarm. But if the bore diameter is close to the control limits and there will be added the average measurement error from several last samples, the value can fall outside the control limits. This scenario can generate another type of alarm, which would inform the operator that the washer is accepted but the true value might be outside the control limits, and that there is a great need to perform very precise measurements for the sake of double check as well as the ring should be marked and measured again at the second station. An example of such control chart is shown in Figure 4.12.

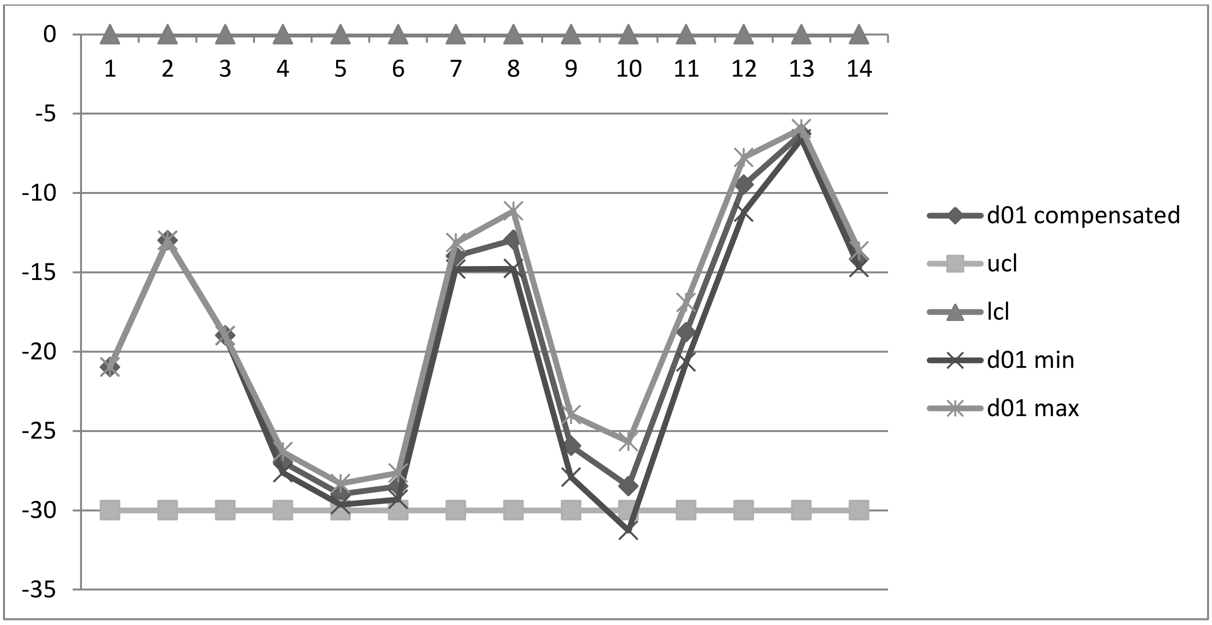


Figure 4.12: Visual example of how a control chart for Measurement station 1 can be used with the feedback from measurement station 2.

The information from the first station control charts will also contain the distance from an average bore diameter to the control limits. This data can be used as a feedback to the assembly area. There this information can be used to influence the control limits for the measurement error. It can be made as simple as the following assumption:

If the hard turning process provides stable results close to the target value the measurement error can be rather big without the risk of true value falling outside the control limits. And if the hard turning process is unstable and the bore diameter is close to the control limits, the measurement process cannot afford a big measurement error and thus there is a greater need for more accurate measurements. So the closer is the bore diameter to the control limits the narrower are the control limits for the measurement.

5. CONCLUSIONS

This is the final chapter of the report; it contains a discussion regarding the fulfillment of the goals set in the purpose of this report as well as reflections upon the work carried out during the course of the project.

5.1 Results

The measurement process that handles the quality control for channel LT5 at SKF Gothenburg is not performing very well. Firstly, it can be seen as very wasteful to measure the same thing twice as it is currently done – this setup has been seen as necessary because of the poor results of the hard turning machine. This setup does indeed minimize the risk of faulty washers being released to the final customer but at the cost of several types of waste especially because of how poorly the measurement process itself performs. The error is so large that it is basically impossible to know for certain whether or not a washer is within specification or not!

At the outset of this project there were speculations that this was due to the charts used to compensate for thermal expansion (or rather shrinkage) as the washers cooled off after the hard turning were simply wrong or used alpha values from a different type of steel. The experiments performed have proven otherwise. We do however recommend that SKF starts using a simple computer aided solution for these calculations as that will provide even better results.

Another possible problem that was investigated was the measurement tools themselves; a pair of SUBITO diameter gages and a Testo 922 Thermometer. All tools passed this test with very good scores indicating that there is something else that causes the variation in measurement results. The PFMEA analysis would indicate that it is instead the environment (physical or psychological) in which the tools are used that is the problem. The operators may well be exposed to a much more stressful surrounding with many different tasks to handle than the selected subjects that did the MSA study. The ergonomics situation for measurements within the hard turning machine may also play a role in the measurement results (the operators have to lean into the machine carefully holding the diameter gage on straight arms) or that the surfaces of the washer inside the machine may be covered with cooling fluid or metal shavings. We have, in the Improvement chapter, suggested a change in tools that handle these situations much better.

We also find it strange for a company like SKF, with a very strong focus on quality and a Six Sigma program that seems to be involving most people in a good way, to not be using the measurement data for anything but a go/no-go type decision. This data could be used for process control by providing for example control charts. Doing that could potentially detect trends in the production and allow for changes in machine settings before the products fall outside the specification limits.

Another thing that we would like to bring up considers learning in the SKF organization. The factories in Gothenburg contain many production channels which have a lot in common. Despite this there seems to be relatively few lessons learnt in other channels that reach across to other locations within the area to benefit the whole organization. The Testo 922 thermometer for example, had recently been replaced in another production channel where it was used to perform the exact same measurement as it was deemed not good enough. This experience seems as if it was unable to reach over to the LT5 production channel despite the two work places exist under the same roof no more than a two minute walk apart. A similar example is the automation of thermal expansion calculations: several production channels seem to have been using spreadsheets for this very application for some time. A third example is how all production channels seem to have had their own ideas on what type of tool to be used for the measurement of diameters (this is a little bit different though, as the tooling required is rather different for different types of rings).

We feel that SKF should consider how knowledge gained at one part of their organization is carried over to other parts, such as for the results of improvement processes covering one production process to another process.

5.2 Reflections: DMAIC and learning

We feel that this project has been rather straight forward. Despite that, we have several times been forced to backtrack and go back to the Define or Measure phases of the DMAIC cycle. This may be due to a less than perfect Define phase that fails to identify the most important aspects of what is, in the end, supposed to be improved – or as we believe to be the case in our project; that it can be near impossible to gain sufficient knowledge about the process without making some measurements and analysis thereof. Conceptually, the image of the PDCL (Plan Do Check Learn) cycle rolling forward describes the work in process improvement very well, see Figure 5.1.

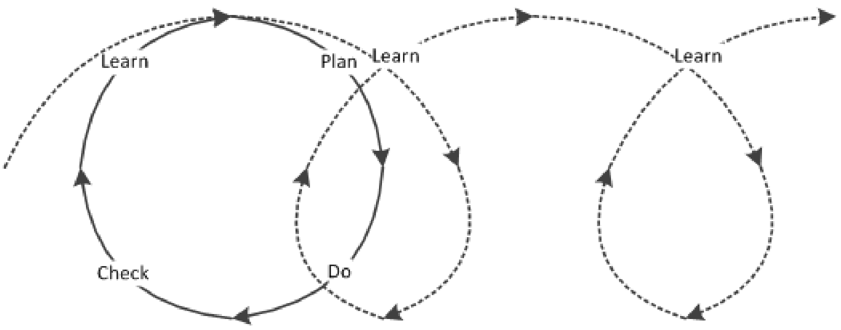


Figure 5.1: The Plan-Do-Check-Learn cycle inspired by Bergman & Klefsjö (2001), in turn inspired by (Deming, 1986).

This puts the focus on learning from the experiences within the project. In a way, the “Do” phase of the PDCL can be seen as most of the DMAIC phases past Define, and whenever something unexpected happens, or when we realize that the definition of the task is not what it should be, we move on to the Check phase thinking “What happened?”. In our project an example can be after performing MSA, the thermal expansion experiment and the data collection and being none the wiser – going back to brainstorm and do a PFMEA helped us redefine the problematic within the process. What we most certainly could have done better is the learning stage of the cycle as our focus directly was on what we should do (i.e. back in the Define or Plan phase) instead of considering why we were forced to rethink.

REFERENCES

Barrentine, L. B. (1991). *Concepts for R&R Studies.* Milwaukee: ASQC Quality Press.

Bergman, B., & Klefsjö, B. (2001). *Kvalitet - Från behov till användning.* Lund: Studentlitteratur.

Bryman, A., & Bell, E. (2007). *Business Research Methods.* Oxford: Oxford University Press.

Carlsson, S. (2011, 04 28). Email: Temperaturkoefficient. Göteborg.

Davidsson, B., & Patel, R. (2003). *Forskningsmetodikens grunder.* Lund: Studentlitteratur.

Deming, W. E. (1986). *Out of the crisis.* Cambridge, Massachusetts: Cambridge University Press.

Groover, M. P. (2010). *Fundamentals of Modern Manufacturing: Materials, Processes and Systems.* Hoboken, NJ: John Wiley & Sons, Inc.

Hammersberg, P. (2011, 05 05). Lecture: Potential Failure Mode and Effect Analysis (p-FMEA). Göteborg.

Hammersberg, P. (2011, 02 01). Lecture: Project charter - High level process map - SIPOC. Göteborg.

Hammersberg, P. (2011, 03 24). Lecture: Qualitative Mapping and Funneling for X-factors. Göteborg.

Jarfors, A. E., Carlsson, T., Nicolescu, C.-M., Rundqvist, B., Keife, H., & Eliasson, A. (2000). *Tillverkningsteknologi.* Lund: Studentlitteratur.

Johansson, G. (2011, 05 23). Meeting: Pugh selection of diameter gauge. Göteborg.

Koepfer, C. (2010, 1 22). Hard Turning as an Alternative to Grinding. *Production Machining*, Accessed on the Internet, 2011-03-17.

Magnusson, K., Kroslid, D., & Bergman, B. (2003). *Six Sigma: The Pragmatic Approach.* Lund: Studentlitteratur.

Nordtec AB. (2011, 05 30). *Nordtec AB*. Retrieved 05 30, 2011, from Nordtec AB: http://nordtec.se/

Perski, A. (2010, 05 17). *Stress.* Retrieved 05 03, 2011, from 1177.se: http://www.1177.se/Fakta-och-rad/Sjukdomar/Stress/

Rislund, C. (2006). *Ergonomi som verktyg.* Göteborg: Chalmers University of Technology.

Sheehy, P., Navarro, D., Silvers, R., Keyes, V., Dixon, D., & Picard, D. (2002). *The Black Belt Memory Jogger: A Pocket Guide for Six Sigma Success.* Salem: GOAL/QPC.

Simon, K. (2010). *SIPOC Diagram*. Retrieved 04 28, 2011, from iSixSigma: http://www.isixsigma.com/index.php?option=com_k2&view=item&id=1013:sipoc-diagram&Itemid=219

SKF AB. (2011, 05 30). *SKF AB*. Retrieved 05 30, 2011, from SKF AB: http://www.skf.com/portal/skf_se/home

Sörqvist, L., & Höglund, F. (2007). *Sex Sigma - Resultatorienterat förbättringsarbete som ger ökad lönsamhet och nöjdare kunder vid produktion av varor och tjänster.* Lund: Studentlitteratur.

Tague, N. R. (2005). *The Quality Toolbox.* Milwakee: American Society for Quality, Quality Press.

Thompson, R. (2007, 06 19). *The Pugh Matrix*. Retrieved 03 30, 2011, from Lean Six Sigma Academy: http://lssacademy.com/2007/06/19/the-pugh-matrix/

Wang, J. X. (2011). *Lean Manufacturing: Business Bottom-Line Based.* Boca Raton: Taylor & Francis.

Womack, J. P., & Jones, D. T. (2003). *Lean Thinking: Banish Waste and Create Wealth in your Corporation.* Free Press: New York.

APPENDIXES

Project charter

Project title:Temperature effect on inner diameter of bearing shaft

Company (organization)	**SKF Sweden AB**	**Unit/Department**	**Large Bearings** **SRTB/Channel LT5**
Executive	**Mattias Lindh**	**Senior Deployment Champion**	-
Deployment Champion	**Michael Jacobson**	**Project Champion**	**Carl-Olof Samuelsson**
Master Black Belt	**Peter Hammersberg**	**Finance Champion**	**Inger Ericsson**
IT Champion	-	**HR Champion**	**Lars Rifve**
Industrial participant (Black Belt candidate)	**Norma Villazon**	**Telephone/e-mail**	**0705573031/** **norma.villazon@skf.com**
Sponsor &process owner	**KostadinKostovski**	**Site or location**	**Gothenburg**
Project Start Date	**01 February 2011**	**Project completion Date**	**25 may 2011**
Expected impact level	-	**Expected financial impact (savings/revenues)**	**150.000 sek/year**

Element	**Description**	**Charter**
1. Project summary	A short description of the project	Improvement of the measurement process by reducing the amount of measurements and increasing the reliability of process output.
2. Impacted process	The specific processes involved in the project	Temperature measurements and the hard turning.

3. Benefit to customers	Define internal and external customers (most critical) and their requirements	Internal: Assembly area. A more stable and reliable process will lead to time savings due to fewer re-measurements as well as less discussion over the impact of measurement and temperature. External: End Customer. Increased customer satisfaction through a lower risk of faulty components being delivered and a better ability to deliver on time.
4. Benefit to the business	Describe the expected improvement in business performance	Lower costs for the channel leading to improved profitability due to less scrap, rework and reduced measuring. Improved ability to deliver on time, to take on emergency orders from customers and a greater certainty that high quality products are delivered.
5. Project delimitations	What will be excluded from the project	The Hard turning is excluded.
6. Required support	Support in terms of resources (human and financial) required for the project	Operators of the LT5 Channel.
7. Team members (including students BB candidates)	Names of the master students who will take part in the project	Björn Friberg, Viacheslav Afanasyev and Norma Villazon
8. Other people involved	List technical experts and other people who will be part of the team	Johan Welinder, Stefan Kimming and Christer Bergagård

		Actual value (baseline)	**Realistic goal by project end date**	**Best case goal**
9. Specific goals	Define the baselines, your realistic goals for the project and the best case targets for improvement.	100% process time	40 % of the process time.	22 % of the process time (saving 300.000 sek/year).

DEFINE phase completion date	**2011-02-24**	MEASURE phase completion date	**2011-03-10**
ANALYZE phase completion date	**2011-04-14**	IMPROVE phase completion date	**2011-05-19**
CONTROL phase completion date	**2011-06-16**	PROJECT results presentation date	**2011-05-25**

S	I		P	O		C
		Requirements			**Requirements**	
Hard turning process	Ring (the component)	-	**Start**: (Measuring begins)			
Diameter gage	Ability to measure diameter	Reliability, ease of use, etc.	Diameter ↓	Measured	-	The process itself
Temperature gage	Ability to measure temperature	Reliability, ease of use, etc.	Temperature ↓	Measured	-	The process itself
Temperature charts (how T affects Ø)	Ability to estimate final Ø based on measurements	Table contains a correct estimation	Estimation of final diameter ↓	Inner diameter measure (Ø$D01_A$)	Reliable, repeatable, etc.	The process itself (due to the second diameter measurement)
			Polishing ↓	Ring polished	No effect on the component (in terms of measurement changes)	The process itself
			Buffer ↓	Buffer	Enough components to provide work for assembly area	Assembly area
Diameter gage	Ability to measure diameter	Reliability, ease of use, etc.	Second diameter measurement ↓	Inner diameter measure (Ø$D01_B$)	Reliable, repeatable, etc.	Assembly station decision making Final customer
			End (Assembly or rejection as scrap/rework)			

Appendix 4.1-2 SIPOC

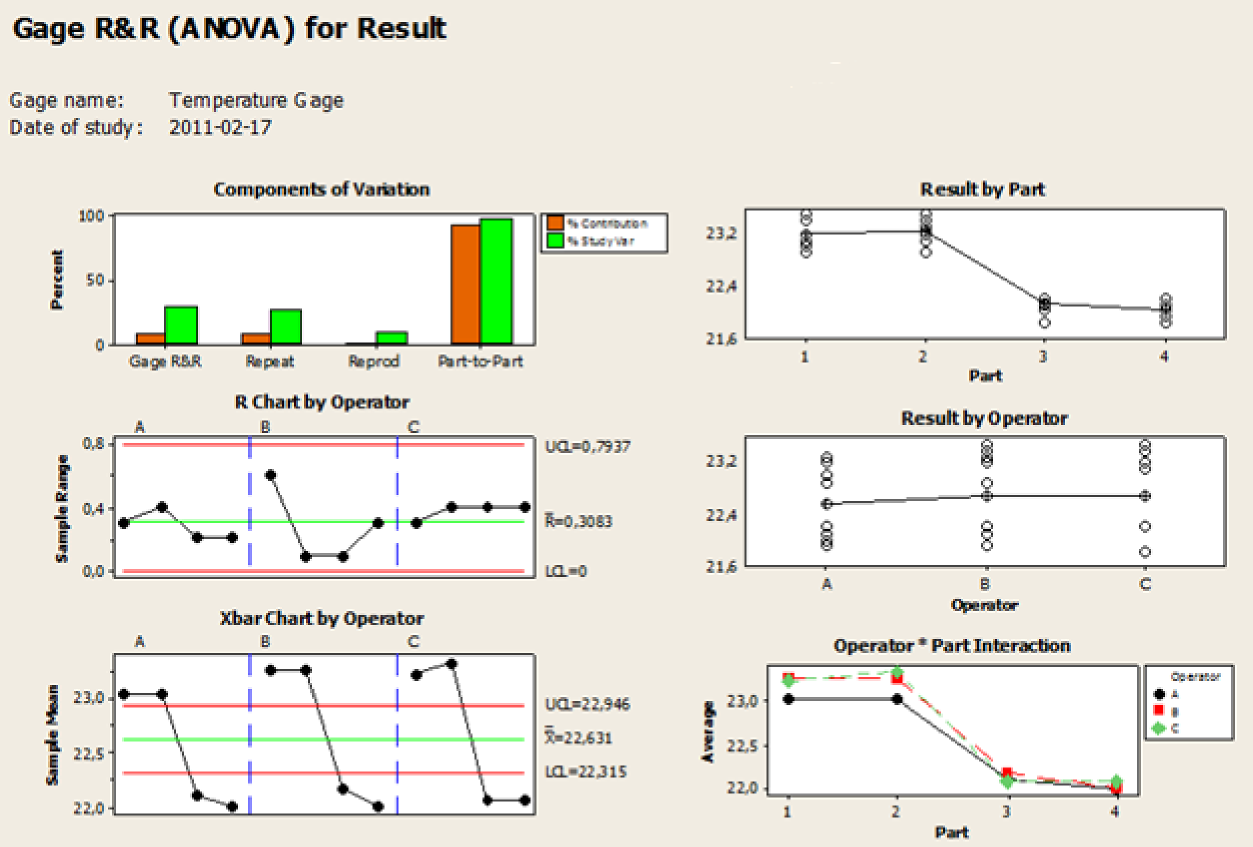
Processmap

Project titel	

Belt:	**BU:**	**Date:**	**Version:**	**Page:** 1

Input	Class	Step	Output	Not
Master ring	!	Calibration of the Subito (Master ring)	Reference point for measurement	
Operator	!			
Subito				
Procedures	!			
Workstation table				
Reference point for measurement	!	Diameter measurement (Washer)	Diameter difference	
Operator	!			
Subito				
Procedures	!			
Washer				
Environment inside the machine				
Termometer	!	Measure the temperature of the master ring	Temperature of the master ring	
Room temperature				
Operator	!			
Procedures	!			
Master ring				
Termometer	!	Measure the temperature of the washer	Temperature of the washer	
Environment inside the machine				
Operator	!			
Procedures	!			
Washer				
Operator		Estimation of the diameter value	Estimated diameter Go/No go decision	
Procedures				
Temperature of the master ring	!			
Temperature of the washer	!			
Diameter difference	!			
Chart (table)	!			
Washer type				

Appendix 4.2-1 Process Mapping



Two-Way ANOVA Table With Interaction

```
Source            DF       SS       MS        F      P
Part               3  11,4875  3,82917  181,382  0,000
Operator           2   0,1422  0,07111    3,368  0,105
Part * Operator    6   0,1267  0,02111    0,618  0,714
Repeatability     24   0,8200  0,03417
Total             35  12,5764


Alpha to remove interaction term = 0,25
```

Two-Way ANOVA Table Without Interaction

```
Source          DF       SS       MS        F      P
Part             3  11,4875  3,82917  121,347  0,000
Operator         2   0,1422  0,07111    2,254  0,123
Repeatability   30   0,9467  0,03156
Total           35  12,5764
```

Gage R&R

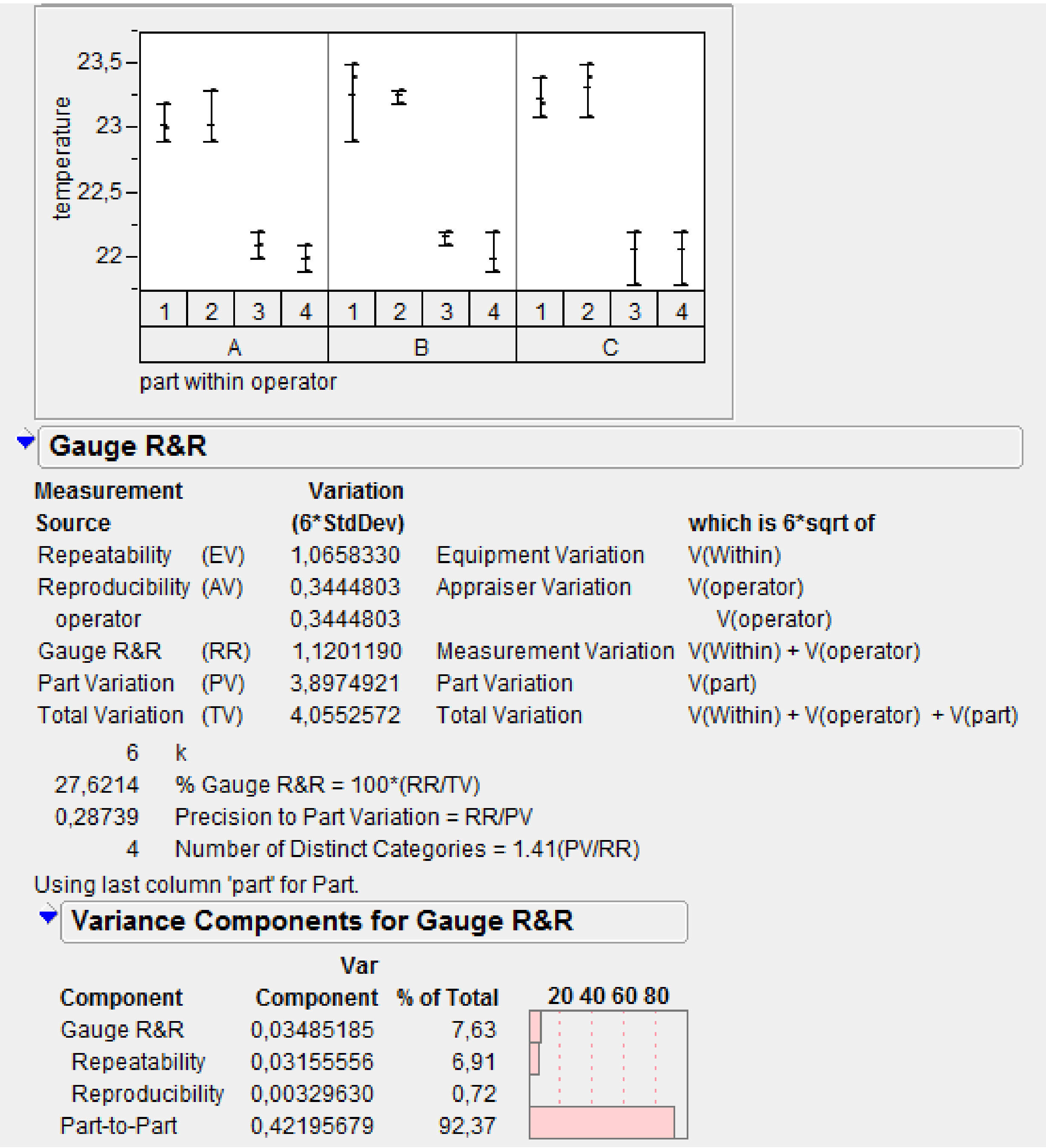
```
                                %Contribution
Source              VarComp     (of VarComp)
Total Gage R&R     0,034852             7,63
  Repeatability    0,031556             6,91
  Reproducibility  0,003296             0,72
```

```
    Operator       0,003296           0,72
Part-To-Part       0,421957          92,37
Total Variation    0,456809         100,00


                                Study Var  %Study Var
Source             StdDev (SD)   (6 * SD)       (%SV)
Total Gage R&R        0,186687    1,12012       27,62
  Repeatability       0,177639    1,06583       26,28
  Reproducibility     0,057413    0,34448        8,49
    Operator          0,057413    0,34448        8,49
Part-To-Part          0,649582    3,89749       96,11
Total Variation       0,675876    4,05526      100,00


Number of Distinct Categories = 4
```

Gage R&R study: Temperature gage



Gauge R&R

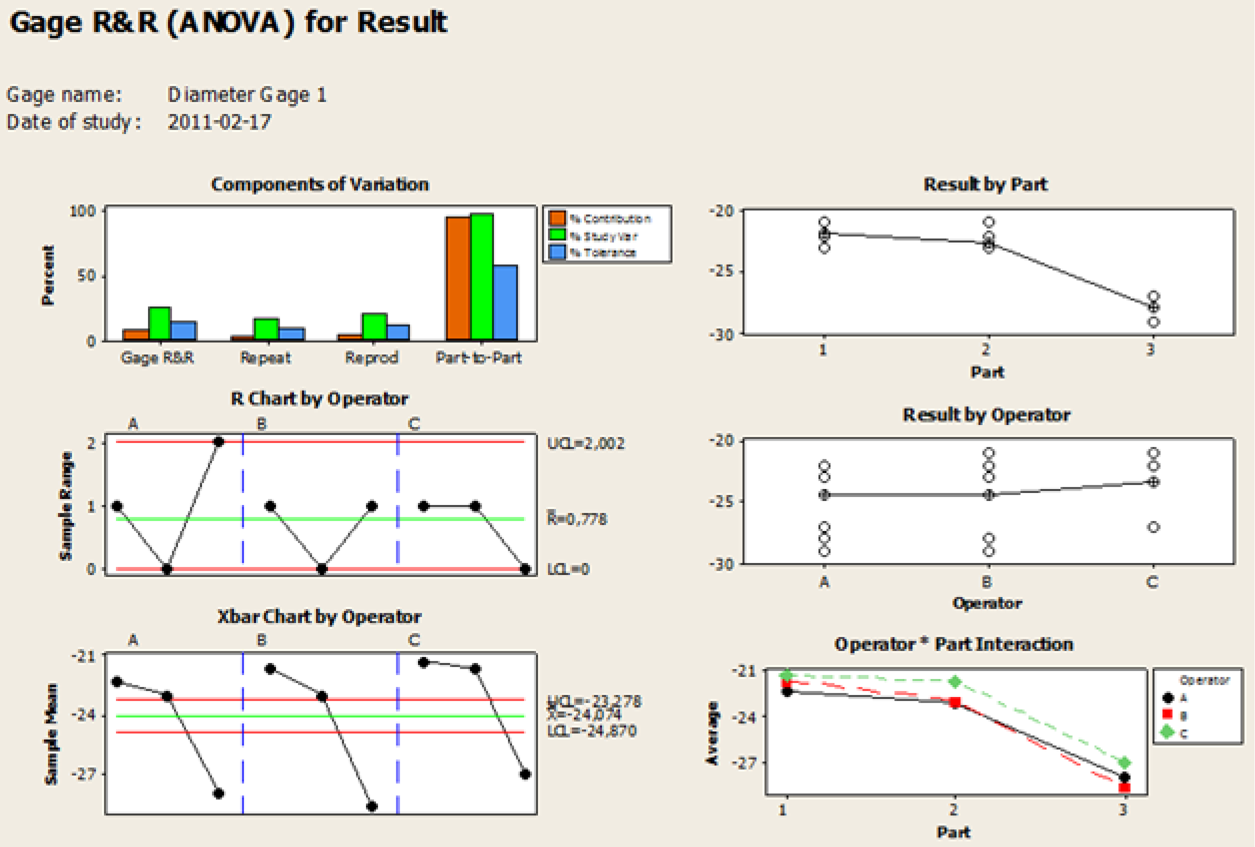
```
Measurement              Variation
Source                   (6*StdDev)                        which is 6*sqrt of
 Repeatability    (EV)   1,0658330   Equipment Variation    V(Within)
 Reproducibility  (AV)   0,3444803   Appraiser Variation    V(operator)
   operator              0,3444803                            V(operator)
 Gauge R&R        (RR)   1,1201190   Measurement Variation  V(Within) + V(operator)
 Part Variation   (PV)   3,8974921   Part Variation         V(part)
 Total Variation  (TV)   4,0552572   Total Variation        V(Within) + V(operator)  + V(part)

        6    k
  27,6214    % Gauge R&R = 100*(RR/TV)
  0,28739    Precision to Part Variation = RR/PV
        4    Number of Distinct Categories = 1.41(PV/RR)

Using last column 'part' for Part.
```

Variance Components for Gauge R&R

```
                            Var
 Component              Component   % of Total
 Gauge R&R             0,03485185         7,63
   Repeatability       0,03155556         6,91
   Reproducibility     0,00329630         0,72
 Part-to-Part          0,42195679        92,37
```



Gage R&R Study - ANOVA Method

```
Gage R&R for Result

Gage name:        Diameter Gage
Date of study:    2011-02-17
Reported by:      Björn Friberg
Tolerance:        -
Misc:             -
```

Two-Way ANOVA Table With Interaction

```
Source           DF       SS       MS        F      P
Part              2  199,185  99,5926  206,846  0,000
Operator          2    7,407   3,7037    7,692  0,043
Part * Operator   4    1,926   0,4815    1,625  0,211
Repeatability    18    5,333   0,2963
Total            26  213,852


Alpha to remove interaction term = 0,25
```

Gage R&R

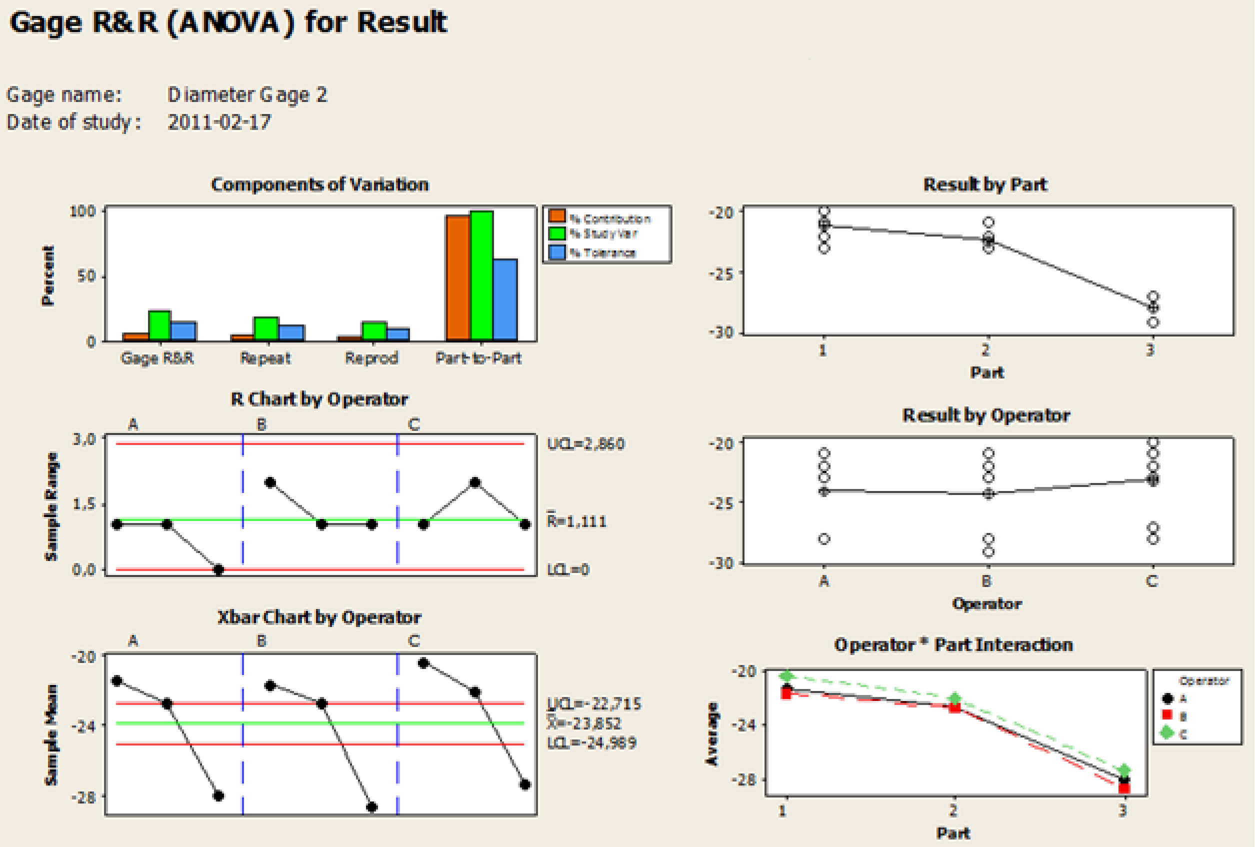
```
                                 %Contribution
Source             VarComp     (of VarComp)
Total Gage R&R      0,7160             6,11
```

```
  Repeatability     0,2963           2,53
  Reproducibility   0,4198           3,58
    Operator        0,3580           3,05
    Operator*Part   0,0617           0,53
Part-To-Part       11,0123          93,89
Total Variation    11,7284         100,00


Process tolerance = 35


                                Study Var  %Study Var  %Tolerance
Source             StdDev (SD)   (6 * SD)       (%SV)  (SV/Toler)
Total Gage R&R         0,84620     5,0772       24,71       14,51
  Repeatability        0,54433     3,2660       15,89        9,33
  Reproducibility      0,64788     3,8873       18,92       11,11
    Operator           0,59835     3,5901       17,47       10,26
    Operator*Part      0,24845     1,4907        7,25        4,26
Part-To-Part           3,31849    19,9109       96,90       56,89
Total Variation        3,42467    20,5480      100,00       58,71


Number of Distinct Categories = 5
```



Gage R&R Study - ANOVA Method

```
Gage R&R for Result

Gage name:        Diameter Gage 2
Date of study:    2011-02-17
Reported by:      Björn Friberg
Tolerance:        -
Misc:             -
```

Two-Way ANOVA Table With Interaction

```
Source           DF       SS       MS        F      P
Part              2  240,296  120,148  811,000  0,000
Operator          2    5,852    2,926   19,750  0,008
Part * Operator   4    0,593    0,148    0,308  0,869
Repeatability    18    8,667    0,481
Total            26  255,407


Alpha to remove interaction term = 0,25
```

Two-Way ANOVA Table Without Interaction

```
Source         DF       SS       MS        F      P
Part            2  240,296  120,148  285,472  0,000
Operator        2    5,852    2,926    6,952  0,005
```

```
Repeatability  22    9,259    0,421
Total          26  255,407
```

Gage R&R

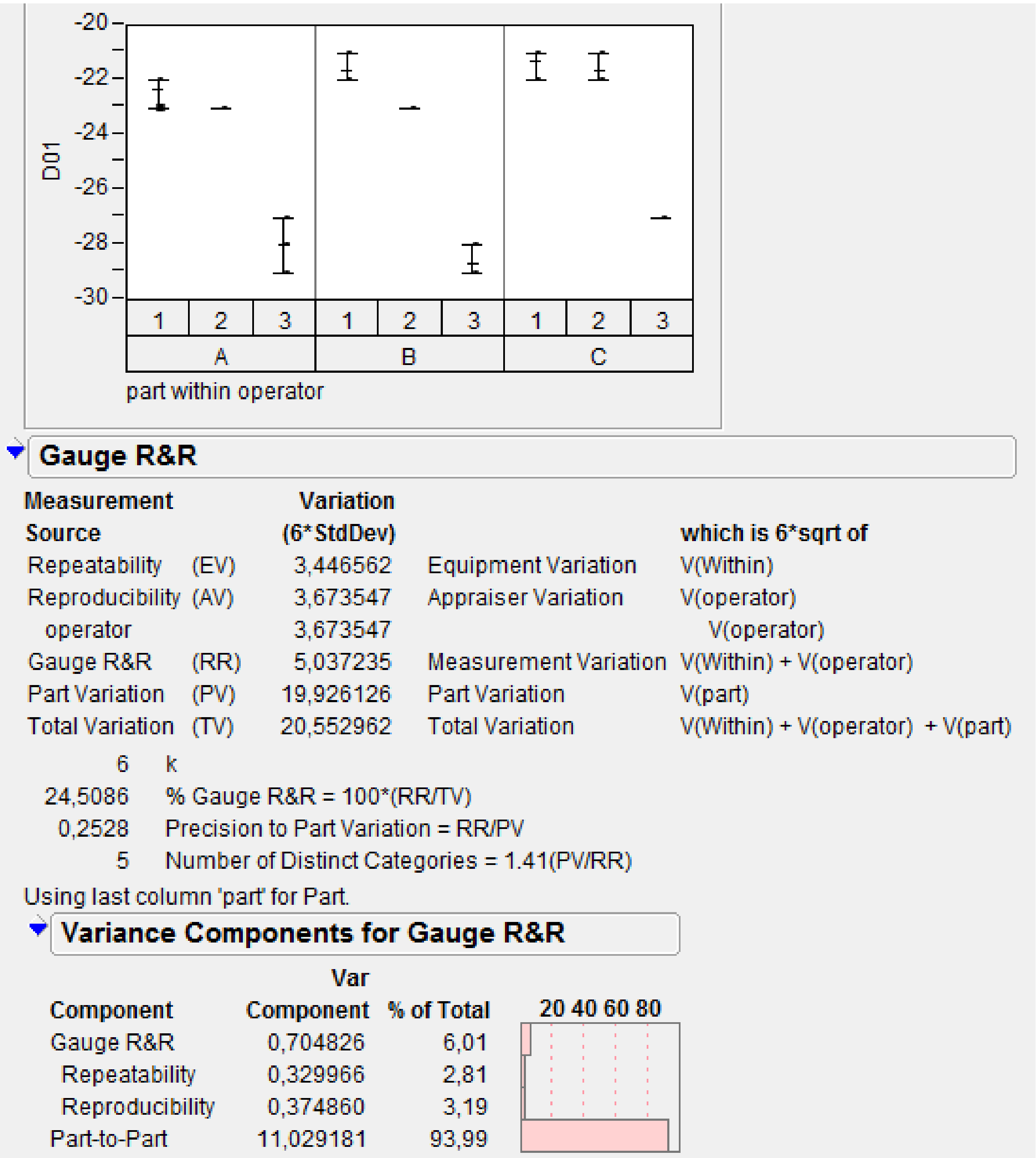
```
                            %Contribution
Source             VarComp   (of VarComp)
Total Gage R&R      0,6992           4,99
  Repeatability     0,4209           3,01
  Reproducibility   0,2783           1,99
    Operator        0,2783           1,99
Part-To-Part       13,3030          95,01
Total Variation    14,0022         100,00


Process tolerance = 35


                                Study Var  %Study Var  %Tolerance
Source             StdDev (SD)   (6 * SD)       (%SV)  (SV/Toler)
Total Gage R&R         0,83619     5,0171       22,35       14,33
  Repeatability        0,64875     3,8925       17,34       11,12
  Reproducibility      0,52758     3,1655       14,10        9,04
    Operator           0,52758     3,1655       14,10        9,04
Part-To-Part           3,64733    21,8840       97,47       62,53
Total Variation        3,74196    22,4517      100,00       64,15


Number of Distinct Categories = 6
```

Gage R&R study: Diameter gage 1



Gauge R&R

Measurement Source		Variation (6*StdDev)		which is 6*sqrt of
Repeatability	(EV)	3,446562	Equipment Variation	V(Within)
Reproducibility	(AV)	3,673547	Appraiser Variation	V(operator)
operator		3,673547		V(operator)
Gauge R&R	(RR)	5,037235	Measurement Variation	V(Within) + V(operator)
Part Variation	(PV)	19,926126	Part Variation	V(part)
Total Variation	(TV)	20,552962	Total Variation	V(Within) + V(operator) + V(part)

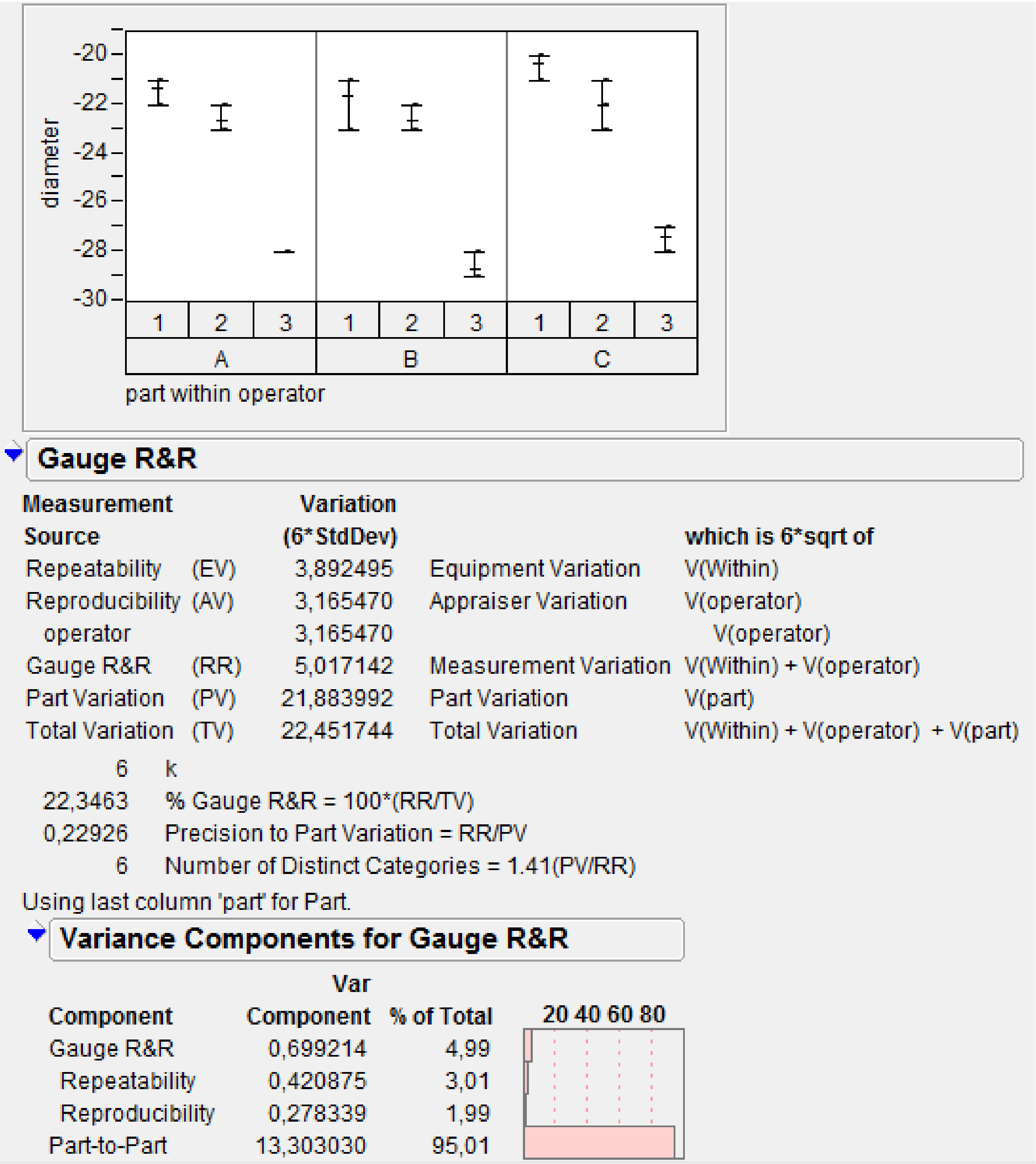
6	k
24,5086	% Gauge R&R = 100*(RR/TV)
0,2528	Precision to Part Variation = RR/PV
5	Number of Distinct Categories = 1.41(PV/RR)

Using last column 'part' for Part.

Variance Components for Gauge R&R

Component	Var Component	% of Total
Gauge R&R	0,704826	6,01
Repeatability	0,329966	2,81
Reproducibility	0,374860	3,19
Part-to-Part	11,029181	93,99

Gage R&R study: Diameter gage 2



Gauge R&R

```
Measurement                Variation
Source                     (6*StdDev)                          which is 6*sqrt of
Repeatability    (EV)       3,892495   Equipment Variation     V(Within)
Reproducibility  (AV)       3,165470   Appraiser Variation     V(operator)
  operator                  3,165470                              V(operator)
Gauge R&R        (RR)       5,017142   Measurement Variation   V(Within) + V(operator)
Part Variation   (PV)      21,883992   Part Variation          V(part)
Total Variation  (TV)      22,451744   Total Variation         V(Within) + V(operator)  + V(part)

        6    k
  22,3463    % Gauge R&R = 100*(RR/TV)
  0,22926    Precision to Part Variation = RR/PV
        6    Number of Distinct Categories = 1.41(PV/RR)

Using last column 'part' for Part.
```

Variance Components for Gauge R&R

Component	Var Component	% of Total
Gauge R&R	0,699214	4,99
Repeatability	0,420875	3,01
Reproducibility	0,278339	1,99
Part-to-Part	13,303030	95,01

Mätinstruktioner (efter svarvning)

Den närmaste tiden kommer det att vara nödvändigt att skriva ner vissa uppmätta värden för den inre diametern för att säkerställa bl.a. att justeringen för temperatur-differens är korrekt.

Tack för hjälpen!

1. Skriv ner detaljens (artikelnummer/identifikation) överst på sidan. Så länge du arbetar med samma typ av detalj fortsätter du på samma sida, men om du byter till en annan modell ska du ta en ny sida.

2. Börja med att markera ringen med det första lediga numret i tabellen. Skriv ner numret på insidan av axelhålet.

3. Mät temperaturerna som vanligt och anteckna resultaten i tabellen.

4. Markera axelhålet med en vertikal linje. Mät ringen (som vanligt) uppe och nere i axelhålet på den plats du markerat med linjen. Anteckna resultaten, och repetera (som vanligt) en gång för varje mått.

5. Anteckna tiden när mätningarna är slutförda.

Mätinstruktioner (innan montering)

Den närmaste tiden kommer det att vara nödvändigt att skriva ner vissa uppmätta värden för den inre diametern för att säkerställa bl.a. att justeringen för temperaturdifferens är korrekt.

Tack för hjälpen!

1. Notera numret som du hittar i detaljens axelhål på en tom rad i tabellen. Finns det inget nummer – hoppa över att anteckna mätdata från denna ring.

2. Anteckna tiden när mätningarna inleds på samma rad.

3. I axelhålet finns även en vertikal linje. Utför diametermätningar på den plats markerad med denna linje, uppe och nere. Repetera en gång för varje mätning och anteckna resultaten i tabellen.

		Hard turning measurements			Assembly measurements			Error
Part #	Target Ø (m)	Temp Δ (K)	Ø (µm)	Ø Estimation (µm)	Temp Δ (K)	Ø (µm)	Ø Estimation (µm)	(HTest - ASSest)
1	0,26	0,8	-26	-28,392	-0,2	-25	-24,402	-3,99
2	0,26	0,3	-20	-20,897	0,3	-22	-22,897	2
3	0,26	1	-10	-12,99	-0,2	-16	-15,402	2,412
4	0,26	0,8	-7	-9,392	-0,5	-15	-13,505	4,113
5	0,26	1,2	-10	-13,588	-0,4	-14	-12,804	-0,784
6	0,26	1	-14	-16,99	-0,3	-18	-17,103	0,113
7	0,26	1,2	-12	-15,588	-0,3	-15	-14,103	-1,485
8	0,26	1,7	-24	-29,083	-0,4	-27	-25,804	-3,279
9	0,26	0,7	-18	-20,093	-0,4	-19	-17,804	-2,289
10	0,26	1	-2	-4,99	-0,5	-10	-8,505	3,515
11	0,26	1,9	-16	-21,681	-0,4	-20	-18,804	-2,877
12	0,26	2	0	-5,98	-0,2	-4	-3,402	-2,578
13	0,26	1,3	-20	-23,887	-0,5	-30	-28,505	4,618
14	0,26	1,2	-24	-27,588	-0,6	-35	-33,206	5,618
15	0,26	1,7	1	-4,083	-0,5	-10	-8,505	4,422
16	0,26	1,1	0	-3,289	-0,6	-13	-11,206	7,917
17	0,26	0,2	-25	-25,598	-0,8	-20	-17,608	-7,99
18	0,26	2	2	-3,98	-0,1	-18	-17,701	13,721
19	0,26	1,7	-13	-18,083	-0,1	-27	-26,701	8,618
31	0,26	1,3	-24	-27,887	0,4	-10	-11,196	-16,691
32	0,26	1,7	-5	-10,083	0,5	-10	-11,495	1,412
33	0,26	1,1	-1	-4,289	0,6	-2	-3,794	-0,495
34	0,26	1,4	-10	-14,186	0,4	-15	-16,196	2,01
35	0,26	2,6	-20	-27,774	0,5	-25	-26,495	-1,279
36	0,26	1,7	-21	-26,083	0,5	-18	-19,495	-6,588
37	0,26	1,1	-1	-4,289	0,7	-5	-7,093	2,804
38	0,26	1,7	-10	-15,083	0,7		-2,093	-12,99
39	0,26	1,6	-8	-12,784	0,9	-10	-12,691	-0,093
40	0,26	1,8	-20	-25,382	0,7	-13	-15,093	-10,289
41	0,26	1,9	-20	-25,681	0,8	-14	-16,392	-9,289
42	0,26	2	-3	-8,98	1,1	-3	-6,289	-2,691
43	0,26	1,6	-23	-27,784	0,2	-28	-28,598	0,814
44	0,26	1,5	-30	-34,485	0,3	-5	-5,897	-28,588
45	0,26	2	-20	-25,98	0,3	-28	-28,897	2,917
46	0,26	2	-20	-25,98	0,2	-20	-20,598	-5,382
47	0,26	1,5	-25	-29,485	0,1	-23	-23,299	-6,186
48	0,26	1,6	-5	-9,784	0,7	-30	-32,093	22,309
49	0,26	2	-15	-20,98	0	-25	-25	4,02
50	0,26	2	-10	-15,98	0,4	-10	-11,196	-4,784
51	0,26	1,5	-12	-16,485	0,5	-15	-16,495	0,01
52	0,26	2	-20	-25,98	0,5	-18	-19,495	-6,485
53	0,26	2	-14	-19,98	0,5	-16	-17,495	-2,485
54	0,26	2	-18	-23,98	0,6	-18	-19,794	-4,186

		Hard turning measurements			Assembly measurements			Error
Part #	Target Ø (m)	Temp Δ (K)	Ø (µm)	Ø Estimation (µm)	Temp Δ (K)	Ø (µm)	Ø Estimation (µm)	(HTest - ASSest)
55	0,26	2	-19	-24,98	0,7	-20	-22,093	-2,887
56	0,26	2,3	0	-6,877	0,5	10	8,505	-15,382
57	0,26	1,5	-20	-24,485	0,7	-20	-22,093	-2,392
58	0,26	2	-10	-15,98	0,6	-16	-17,794	1,814
59	0,26	1,5	-14	-18,485	0,1	-12	-12,299	-6,186
60	0,26	1,5	-15	-19,485	0,1	-8	-8,299	-11,186
61	0,26	1,7	-10	-15,083	0,1	-16	-16,299	1,216
62	0,26	1,5	-15	-19,485	0,2	-22	-22,598	3,113
63	0,26	2	-17	-22,98	0,1	-28	-28,299	5,319
64	0,26	2	-20	-25,98	0,2	-28	-28,598	2,618
65	0,26	1,5	-14	-18,485	0,1	-25	-25,299	6,814
66	0,26	1,5	-16	-20,485			0	-20,485
67	0,26	2	-16	-21,98	0,1	-28	-28,299	6,319
68	0,26	2	-15	-20,98	0,1	-22	-22,299	1,319
69	0,26	1,5	-5	-9,485	0,2	-10	-10,598	1,113
70	0,26	1,8	-10	-15,382	0,4	-18	-19,196	3,814
71	0,26	3	-3	-11,97	0,2	-10	-10,598	-1,372
72	0,26	2	-10	-15,98	0,1	-29	-29,299	13,319
73	0,26	1	-20	-22,99	0,3	-19	-19,897	-3,093
74	0,26	1,5	-2	-6,485	0,3	-2	-2,897	-3,588
75	0,26	2	-20	-25,98	0,5	-28	-29,495	3,515
76	0,26	2,2	-15	-21,578	0,5	-12	-13,495	-8,083
77	0,26	1,5	-20	-24,485	0,7	-30	-32,093	7,608
78	0,26	1,8	-18	-23,382	2	-12	-17,98	-5,402
79	0,26	1	-27	-29,99			0	-29,99
80	0,26	2,2	-22	-28,578	2	-20	-25,98	-2,598
81	0,26	2,5	-19	-26,475			0	-26,475
82	0,26	2,2	-20	-26,578	-0,3	-22	-21,103	-5,475
83	0,26	2	-10	-15,98			0	-15,98
84	0,26	-1,5	-25	-20,515	1	-15	-17,99	-2,525
85	0,26	-1,5	-20	-15,515	1,1	-12	-15,289	-0,226
86	0,26	-2	-15	-9,02	0,6	-15	-16,794	7,774
87	0,26	2,3	-15	-21,877	0,8	-16	-18,392	-3,485
88	0,26	2	-25	-30,98	0,6	-25	-26,794	-4,186
89	0,26	2	-20	-25,98	0,7	-25	-27,093	1,113
90	0,26	2,3	0	-6,877	1	-2	-4,99	-1,887
91	0,26	1	-16	-18,99	0,2	-12	-12,598	-6,392
92	0,26	2	-5	-10,98	0,4	-5	-6,196	-4,784
93	0,26	2,5	-10	-17,475	0,5	-10	-11,495	-5,98
94	0,26	2,1	-20	-26,279	0,6	-28	-29,794	3,515
95	0,26	2,6	-11	-18,774	0,3	-10	-10,897	-7,877
96	0,26	2,2	-25	-31,578	0,7	-21	-23,093	-8,485
97	0,26	2,3	-20	-26,877	0,8	-20	-22,392	-4,485

		Hard turning measurements			Assembly measurements			Error
Part #	Target Ø (m)	Temp Δ (K)	Ø (µm)	Ø Estimation (µm)	Temp Δ (K)	Ø (µm)	Ø Estimation (µm)	(HTest - ASSest)
98	0,26	2	-16	-21,98	1	-10	-12,99	-8,99
99	0,26	1,4	-23	-27,186	0,7	-9	-11,093	-16,093
100	0,26	1,5	-7	-11,485	2,3	0	-6,877	-4,608
101	0,26	2,1	-14	-20,279	2,4	-12	-19,176	-1,103
102	0,26	1,7	-19	-24,083	2,2	-5	-11,578	-12,505
103	0,26	1,9	-2	-7,681	1	-30	-32,99	25,309
104	0,26	0,9	-15	-17,691	0,8	-32	-34,392	16,701
105	0,26	1,4	-12	-16,186	0,7	-30	-32,093	15,907
106	0,26	1,2	-16	-19,588	0,3	-30	-30,897	11,309
107	0,26	1,7	-13	-18,083	0,5	-27	-28,495	10,412
108	0,26	2	-15	-20,98	0,3	-36	-36,897	15,917
109	0,26	2,1	-23	-29,279	0,6	-30	-31,794	2,515
110	0,26	1,3	-18	-21,887	0,5	-30	-31,495	9,608
111	0,26	1,8	-20	-25,382	0,6	-32	-33,794	8,412
112	0,26	1,9	-14	-19,681	0	-27	-27	7,319
113	0,26	2,3	-25	-31,877	0	-15	-15	-16,877
114	0,26	2,1	-20	-26,279	0	-28	-28	1,721
115	0,26	1,9	-25	-30,681	0	-22	-22	-8,681
116	0,26	2	-10	-15,98	-0,3	-23	-22,103	6,123
117	0,26	1,2	-10	-13,588	-0,3	-24	-23,103	9,515
118	0,26	2	-24	-29,98	0	-34	-34	4,02
119	0,26	2	-20	-25,98	0	-25	-25	-0,98
120	0,26	2	-16	-21,98	0,1	-21	-21,299	-0,681
121	0,26	0,5	-13	-14,495	-0,5	-15	-13,505	-0,99
122	0,26	1,7	-3	-8,083	-0,7	-10	-7,907	-0,176
123	0,26	1,4	-18	-22,186	-0,7	-16	-13,907	-8,279
124	0,26	1,2	-11	-14,588	-0,6	-15	-13,206	-1,382
125	0,26	1	-15	-17,99	-1,7	-22	-16,917	-1,073
126	0,26	1,2	-9	-12,588	-1,6	-20	-15,216	2,628
127	0,26	1,4	-16	-20,186	-1,5	-25	-20,515	0,329
128	0,26	1,2	-16	-19,588	-1,1	-26	-22,711	3,123
129	0,26	1,4	-5	-9,186	-1,4	-16	-11,814	2,628
130	0,26	2,2	-10	-16,578	-1,2	-26	-22,412	5,834
131	0,26	2	-23	-28,98	-1,2	-29	-25,412	-3,568
132	0,26	2	-14	-19,98	-1	-22	-19,01	-0,97
133	0,26	2	-19	-24,98	-1	-29	-26,01	1,03
134	0,26	2	-19	-24,98	-1	-30	-27,01	2,03
135	0,26	2,1	-12	-18,279	-1	-22	-19,01	0,731
136	0,26	2	-15	-20,98	-0,9	-29	-26,309	5,329
137	0,26	2	-10	-15,98	-1	-18	-15,01	-0,97
138	0,26	2	-8	-13,98	-0,3	-18	-17,103	3,123
139	0,26	2	-14	-19,98	-0,4	-18	-16,804	-3,176
140	0,26	2,4	-13	-20,176	-0,2	-22	-21,402	1,226

		Hard turning measurements			Assembly measurements			Error
Part #	Target Ø (m)	Temp Δ (K)	Ø (µm)	Ø Estimation (µm)	Temp Δ (K)	Ø (µm)	Ø Estimation (µm)	(HTest - ASSest)
141	0,26	2	-16	-21,98	-0,2	-22	-21,402	-0,578
142	0,26	2	-3	-8,98	-0,1	-16	-15,701	6,721
143	0,26	2	-18	-23,98	-0,1	-25	-24,701	0,721
144	0,26	1,7	-19	-24,083	-0,2	-20	-19,402	-4,681
145	0,26	1,7	-23	-28,083	-0,2	-23	-22,402	-5,681
146	0,26	1,7	-16	-21,083	-0,2	-25	-24,402	3,319
147	0,26	1,7	-20	-25,083	0,3	-22	-22,897	-2,186
148	0,26	1,8	-23	-28,382	0	-25	-25	-3,382
149	0,26	1,6	-20	-24,784	0	-15	-15	-9,784
150	0,26	1,6	-22	-26,784	-0,2	-28	-27,402	0,618

Data set 1	Temp ref	Temp exp	Δ temp.	Δ diam.	Calculated	Deviation
25	21,7	24,6	2,9	3	0	-3
24	21,65	24,55	2,9	3	0	-3
23	21,6	24,7	3,1	4	0	-4
22	21,6	24,7	3,1	4	0	-4
21	21,5	24,75	3,25	4	0	-4
20	21,4	24,95	3,55	5	0	-5
19	21,4	25,05	3,65	5	0	-5
18	21,3	25,1	3,8	6	0	-6
17	21,2	25,3	4,1	7	0	-7
16	21,2	25,35	4,15	7	0	-7
15	21,2	25,45	4,25	7	0	-7
14	21,1	25,5	4,4	8	0	-8
13	21,05	25,7	4,65	8	0	-8
12	21,05	25,85	4,8	9	0	-9
11	21	26	5	9	0	-9
10	21	26,1	5,1	10	0	-10
9	20,85	26,4	5,55	11	0	-11
8	20,7	26,65	5,95	11	0	-11
7	20,6	27	6,4	12	0	-12
6	20,3	27,65	7,35	13	0	-13
5	20,3	27,95	7,65	15	0	-15
4	20,1	28,2	8,1	16	0	-16
3	19,95	28,35	8,4	18	0	-18
2	19,85	28,8	8,95	20	0	-20
1	19,55	29,55	10	24	0	-24

Data set 2	Temp ref	Temp exp	Delta T	Delta D	Calculated	Deviation
1	22,4	18,9	-3,5	-13	0	13
2	22,8	18,2	-4,6	-17	0	17
3	23	18	-5	-16	0	16
4	22,7	17,8	-4,9	-17	0	17
5	22,8	18,1	-4,7	-17	0	17
6	23	18,6	-4,4	-16	0	16
7	22,9	18,5	-4,4	-16	0	16
8	22,8	18,8	-4	-15	0	15
9	22,6	19,1	-3,5	-14	0	14
10	22,5	19,3	-3,2	-12	0	12
11	22,5	19,5	-3	-12	0	12
12	22,5	19,6	-2,9	-12	0	12
13	22,5	19,7	-2,8	-12	0	12
14	21,5	20,6	-0,9	-7	0	7
15	21,5	20,5	-1	-7	0	7

Data set 3	Temp ref	Temp exp	Delta T	Delta D	Calculated	Deviation
1	6,1	6,1	0	-4	0	4
2	8,2	8,2	0	-4	0	4

Appendix 4.2-5 Thermal expansion experiment results

	Process Step	Input	Potential Failure Mode	Potential Effect(s) of Failure	SEV	Potential Cause(s)/Mechanisms of Failure	OCC	Current Process Controls Detection	DET	RPN	Recommended Actions(s)	SEV	OCC	DET	RPN	IMP
1	Calibration of the SUBITO	Master ring	Poorly calibrated SUBITO	Wrong decision about the washer	10	Poorly calibrated master ring	1	Calibration	1	**10**	Nothing	10	1	1	**10**	
2	Calibration of the SUBITO	Operator	Poorly calibrated SUBITO	Wrong decision about the washer	7	Lack of attention	7	None	10	**490**	Change of tool to one that is less affected by variations in use	1	7	10	**70**	**420**
3	Calibration of the SUBITO	Operator	Poorly calibrated SUBITO	Wrong decision about the washer	10	Lack of skill	4	GBO: Groupbased organisation	1	**40**	Nothing	10	4	1	**40**	
4	Calibration of the SUBITO	SUBITO	Poorly calibrated SUBITO	Wrong decision about the washer	4	Sensitive to variation in use	10	MSA	7	**280**	Change of tool to one that is less affected by variations in use	1	1	7	**7**	**273**
5	Calibration of the SUBITO	Procedures	Poorly calibrated SUBITO	Wrong decision about the washer	7	The SUBITO is not calibrated as it is seen as too time consuming or unneccesary	4	None	10	**280**	Simplify the procedures. Poka Yoke (procedures that has to be followed in order to make the process move forward)	7	1	4	**28**	**252**
6	Calibration of the SUBITO	Procedures	Poorly calibrated SUBITO	Wrong decision about the washer	7	The SUBITO is not calibrated as procedures are not understood	1	None	10	**70**	Nothing	7	1	10	**70**	
7	Diameter measurement	Environment inside the machine	Bad readings	Wrong decision about the washer	10	Scrap metal gets in the way	4	Procedures (clean out the washer shaft before measuring)	7	**280**	A tool that measures in more than one place can eliminate the risk of measuring in a location with fragments of scrap metal	10	1	4	**40**	**240**
8	Measure the temperature of the master ring	Thermometer	Wrong temperature reading	Wrong decision about the washer	4	Low accuracy of the thermometer	10	None	10	**400**	More accurate thermometer	1	1	10	**10**	**390**
9	Measure the temperature of the master ring	Thermometer	Wrong temperature reading	Wrong decision about the washer	7	Problems with the contact sensor	4	Visual inspection	7	**196**	More protected sensors, visual control system	7	1	4	**28**	**168**
10	Measure the temperature of the master ring	Operator	Wrong temperature reading	Wrong decision about the washer	4	Lack of attention	7	None	10	**280**	Elimination of the human factor (magnet attachment, automatic reading)	1	1	10	**10**	**270**
11	Measure the temperature of the master ring	Procedures	Wrong temperature reading	Wrong decision about the washer	4	Either temperature not measured as it is seen as too time consuming or unneccessary	4	None	10	**160**	Poka yoke, automation	4	1	1	**4**	**156**
12	Estimation of the diameter value	Adjustment charts	Wrong temperature compensation	Wrong decision about the washer	10	Formulas used do not match theory	10	None	10	**1000**	Formulas corrected to match theory, if needed	1	1	1	**1**	**999**
13	Estimation of the diameter value	Adjustment charts	Wrong temperature compensation	Wrong decision about the washer	10	Theoretical formulas do not match reality	10	None	10	**1000**	Experiments to make certain that theory matches reality	1	1	1	**1**	**999**
14	Estimation of the diameter value	Adjustment charts	Wrong temperature compensation	Wrong decision about the washer	4	Reading the wrong table	4	Double check that the right page is used	4	**64**	Nothing	4	4	4	**64**	
15	Estimation of the diameter value	Adjustment charts	Wrong temperature compensation	Wrong decision about the washer	4	Reading the wrong line	4	None	10	**160**	Automatization of calculations	1	1	1	**1**	**159**
16	Estimation of the diameter value	Adjustment charts	Wrong temperature compensation	Wrong decision about the washer	1	Poor resolution of the tables	10	None	10	**100**	Automatization of calculations	1	1	1	**1**	**99**
17	Estimation of the diameter value	Operator	Wrong temperature compensation	Wrong decision about the washer	7	Wrong calculations	4	None	10	**280**	Automatization of calculations	10	1	10	**100**	**180**
18	Estimation of the diameter value	Procedures	Wrong temperature compensation	Wrong decision about the washer	1	Skip reading the charts	10	None	10	**100**	Automatization of calculations	1	1	1	**1**	**99**