

DOKUZ EYLUL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

**USE OF SIX SIGMA METHOD AS A PROCESS
IMPROVEMENT TECHNIQUE**



by
Atakan GERGER

December, 2017
İZMİR

USE OF SIX SIGMA METHOD AS A PROCESS IMPROVEMENT TECHNIQUE

**A Thesis Submitted to the
Graduate School of Natural and Applied Sciences of Dokuz Eylül University
In Partial Fulfillment of the Requirements for the Degree of Doctor of
Philosophy in Statistics Program**

**by
Atakan GERGER**

**December, 2017
İZMİR**

Ph.D. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled “USE OF SIX SIGMA METHOD AS A PROCESS IMPROVEMENT TECHNIQUE” completed by ATAKAN GERGER under supervision of ASSOC. PROF. DR. ALİ RIZA FİRUZAN and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Doctor of Philosophy.



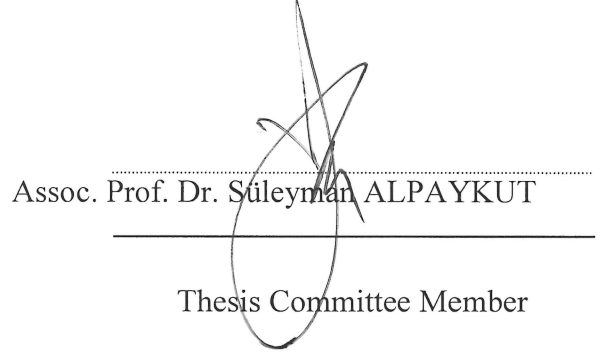
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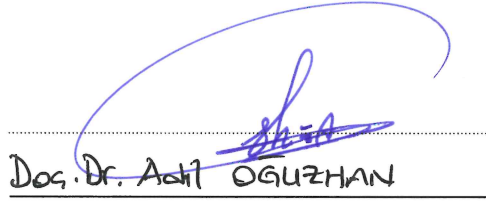
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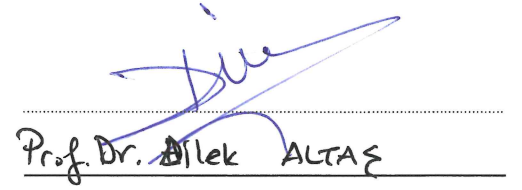
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ACKNOWLEDGMENTS

I would like to say thank Department of Statistics at Dokuz Eylül University of Turkey for making my doctoral study an unforgettable and valuable experience.

Foremost, I would like to express my gratitude to my Ph.D. supervisor Assoc. Prof. Dr. Ali Rıza FİRUZAN for his great help, support, and productive criticism. He gives a fillip to me to progress his ideas. Furthermore, he did not only supervise my thesis but also he was constantly concerned in mine personal life. I am thankful to Prof. Dr. Ali Kemal Şehirlioğlu, and Assoc. Prof. Dr. Süleyman Alpaykut, who served on my dissertation committee and provided their knowledge and support to this effort. Additionally, I wish to thank Prof. Dr. Cenk Özler, Asst. Prof. Dr. Murat Tanık and Asst. Prof. Dr. Bayram Çetin for their constant fortification and support all throughout the study.

I am thankful to rubber producer, the manufacturing firm which bountifully provided the data for the industrial case-study presented in mine thesis and for contributing a lot of factory visits and interviews with their related managers and other correspondents.

I would like to convey special thanks to my core family members. My wife, Assoc. Prof. Dr. Güneş Çetin Gerger, never gave up on me when I was about to give up on myself. She provided words of help, gave me guidance, pushed me when I needed to be pushed, and sacrificed to make sure I could proceed my academic accomplishments. Without her support, I would have never ended my doctoral journey. I also want to take my son, Eren Alp. He each had to bear time when I could not spend time being a dad and had to spend time being a student. Without their understanding and support, this would have been much more complex.

As a result, I want to thank all other my friends and remaining household members like my father is Mustafa and mother is Münevver for their encouragement and support.

Atakan GERGER

USE OF SIX SIGMA METHOD AS A PROCESS IMPROVEMENT TECHNIQUES

ABSTRACT

This thesis suggested a conceptual Six Sigma/DOE hybrid framework aiming to integrate Taguchi methods and Six Sigma for process improvement in a complex industry environment. The studies employing the Taguchi experiment design usually focus on a single variable and neglect the effects of the adjustments on remaining quality characteristics, in this study a multi-response experiment design was preferred and all of the quality characteristics are taken into account.

The aim of this study is the implementation of Six Sigma methodology on a company operating within the automotive industry and the statistical evaluation of the methodological effects on the performance of the enterprise. This Six Sigma study was conducted to improve the manufacturing process which caused a customer complaint within the company.

DMAIC phases are used to reduce the nonconformity rate from 23.940 percentage (baseline) to 0.049 percentage. As the result of implementing SS, the sigma level increased from 2.21 (baseline) to 4.80.

Keywords: Six sigma, Multi response Taguchi design of experiment, Measurement system analyze, Statistical process control, DMAIC, Industrial statistics application

ALTI SİGMA YÖNTEMİNİN SÜREÇ İYİLEŞTİRME TEKNİĞİ OLARAK KULLANILMASI

ÖZ

Bu uygulama çalışması, karmaşık bir endüstri ortamında süreç iyileştirmesi için Taguchi deney tasarımı ve Altı Sigma yöntemini bütünleştirmeyi hedefleyen bir kavramsal Altı Sigma/DOE hibrit çerçeve ileri sürmektedir. Taguchi deney tasarımının kullanıldığı çalışmalarda genellikle tek bir değişken üzerine odaklanırken ve yapılan değişikliklerin diğer kalite karakteristikleri üzerindeki etkisi göz ardı edilirken, bu çalışmada çok yanıtlı Taguchi deney tasarımı tercih edilmiş ve tüm kalite karakteristikleri dikkate alınmıştır.

Bu uygulama çalışmasının amacı; otomotiv sektöründe faaliyet gösteren bir firmada Altı Sigma yönteminin uygulanması ve kuruluşun performansı üzerindeki metodolojik etkilerin istatistiksel değerlendirilmesidir. Bu Altı Sigma çalışması; müşteri şikayetine neden olan üretim prosesinin iyileştirilmesi için gerçekleştirilmiştir.

DMAIC aşamaları, uygunsuz ürün yüzdesini 23.940 seviyesinde (başlangıç seviyesi) yüzde 0.04 seviyesine indirmek için kullanılmıştır. Altı Sigma uygulamasının sonucu olarak; sigma seviyesi 2.21'den (başlangıç seviyesi) 4.80'e yükselmiştir.

Keywords: Altı sigma, Çok yanıtlı Taguchi deney tasarımı, Ölçüm sistem analizi, İstatistiksel süreç kontrol, DMAIC, Endüstriyel istatistik uygulamaları

CONTENTS

	Page
THESIS EXAMINATION RESULT FORM	ii
ACKNOWLEDGMENTS	iii
ABSTRACT	iv
ÖZ	v
LIST OF FIGURES	viii
LIST OF TABLES	x
CHAPTER ONE – INTRODUCTION	1
1.1 Introduction	1
1.2 Scope of the Research	1
1.3 Research Aims and Objectives	2
1.4 Structure Of The Thesis.....	3
CHAPTER TWO – SIX SIGMA	4
2.1 Introduction	4
2.2 Six Sigma Approach.....	4
2.3 The History of Six Sigma	6
2.4 The Benefits of Six Sigma.....	11
2.5 Six Sigma Team Roles	13
2.6 DMAIC Methodology	16
2.7 Success Factors for Six Sigma Projects.....	19
2.8 Statistical Theory of Six Sigma.....	22
2.9 1.5 Sigma Shift	35
CHAPTER THREE – APPLICATION	39
3.1 Scope of Project	39

3.2 Company Information About the Application.....	39
3.3 Purpose of Application.....	40
3.4 Application Method.....	41
3.5 Application Phases	42
3.5.1 Define Phase	42
3.5.2 Measure Phase	44
3.5.3 Analyze Phase.....	61
3.5.4 Improve Phase	71
3.5.5 Control Phase.....	92
CHAPTER FOUR – CONCLUSION.....	101
REFERENCES.....	106
APPENDICES	117

LIST OF FIGURES

	Page
Figure 2.1 Performance improvement roles.....	14
Figure 2.2 Variation: Common cause	23
Figure 2.3 Variation: Special causes.....	24
Figure 2.4 Segmented bell-shaped curve	25
Figure 2.5 Normal distribution.....	26
Figure 2.6 Left skewness or negative distribution	27
Figure 2.7 Right skewness or positive distribution.....	28
Figure 2.8 Kurtosis frequency types	29
Figure 2.9 Various C_p levels	31
Figure 2.10 Various C_{pk} levels.....	32
Figure 2.11 Sigma quality levels of 6σ and 3σ	37
Figure 2.12 Impacts of a 1.5σ shift of process mean when the 6σ quality level is achieved	37
Figure 3.1 Educational level of rubber producer company's.....	40
Figure 3.2 Project schedule	43
Figure 3.3 Location of the front door glass seal on a vehicle	45
Figure 3.4 Flexibility test	46
Figure 3.5 Gage R & R data normality test.....	48
Figure 3.6 Gage R & R analysis result.....	49
Figure 3.7 Cause and effect analysis of the measurement system errors.....	53
Figure 3.8 Normality test for new measurement result.....	57
Figure 3.9 Gage R&R analysis results of the new measurement results	58
Figure 3.10 Result of normality test.....	63
Figure 3.11 $\bar{X} - R$ control chart.....	64
Figure 3.12 Process capability analysis	65
Figure 3.13 Comparation of tolerance limits	67
Figure 3.14 Ishikawa diagram for process incapability	68
Figure 3.15 Main effects plot for S/N ratio value on factors	84
Figure 3.16 Control phase.....	92

Figure 3.17 Normality test for improved result	94
Figure 3.18 $\bar{X} - R$ chart	95
Figure 3.19 Process capability index	96
Figure 3.20 Comparison of natural tolerance limits with specification and control limits	97
Figure 3.21 Comparison of before and after quantities	98
Figure 3.22 Comparison of before and after profit.....	99



LIST OF TABLES

	Page
Table 2.1 Rating of process improvement techniques	10
Table 2.2 Human and process aspects of improvement.....	13
Table 2.3 Nine team roles	20
Table 2.4 C_p values	31
Table 2.5 C_{pk} values.....	33
Table 2.6 Setting capability goals	34
Table 2.7 Relationship between C_p , C_{pk} and Sigma level	35
Table 2.8 PPM changes when sigma quality level changes.....	38
Table 3.1 Gage R&R measurement result.....	48
Table 3.2 Gage R&R Study – Anova.....	51
Table 3.3 New Gage R&R results.....	56
Table 3.4 Gage R&R Study – ANOVA for new data.....	60
Table 3.5 Result of measurements per shift.....	62
Table 3.6 Factors affecting the flexibility of the glass seals.....	71
Table 3.7 Suitable orthogonal arrays OA (27, 3 ⁶).....	73
Table 3.8 Signal/noise result for flexibility	76
Table 3.9 Signal/noise result for view	77
Table 3.10 Signal/noise result for weight	78
Table 3.11 Signal/noise result for hardness	79
Table 3.12 Data summary by experiment	81
Table 3.13 S/N ratio value by factor level	83
Table 3.14 Anova results for response variables	85
Table 3.15 Confirmation experiment results per response variable.....	87
Table 3.16 Compare of confirmation data's with starting condition, best 10 condition and optimum condition.....	88
Table 3.17 According to normalized costs (C_{ij}) TNQL and MRSN values	89
Table 3.18 S/N ratios according to the non-normalized costs	90
Table 3.19 Before-after comparison	92

Table 3.20 Data after improvement	93
Table 3.21 Comparison of before-project and after-project	99
Table 4.1 Comparison of confirmation data with the initial condition and the optimal condition	103



CHAPTER ONE

INTRODUCTION

1.1 Introduction

Quality is a standard, which many companies strive to achieve. While quality is an essential fact for the manufacturers from this aspect, it is also a lifestyle for the consumers. Therefore, customer satisfaction is the top priority for production organizations. The success of an organization depends on achieving the highest quality with the lowest possible costs in the shortest possible time.

Modern industrial companies are in need of good process management and continuous improvement in order to acquire an advantageous position among the competition and to achieve customer satisfaction at the same time. To this end, companies employ methods and techniques featuring a series of statistical and non-statistical tools. One of these numerous techniques is the Six Sigma approach.

Six Sigma, today, is applied successfully in many fields such as services and public sector, following a rapid expansion from the point it was introduced for the first time in an industrial environment at Motorola in 1980's. In this study, Six Sigma and Taguchi experiment design are combined and analyzed as a case of implementation in the automotive sector.

1.2 Scope of the Research

This research was positioned in the scope of Six Sigma methodology and application in the production industry. The scope of this research is described below:

- The study focused on the application of Six Sigma in the manufacturing industry, including approaches such as Measurement System Analyze (Gage R&R), Statistical Process Control (SPC), process optimization and Taguchi Design of Experiment.

- The Six Sigma methodology used for the process improvement at a manufacturer of rubber and rubber derivative products for the automotive industry constitutes the scope of the application.

In view of the highly competitive nature of the automotive industry, the rubber manufacturing company desires the enterprise information to be considered confidential, and as a consequence, no company information is disclosed in this study.

1.3 Research Aim and Objectives

This research aimed to explore how manufacturing company adopts Six Sigma methodologies for improving product quality, to intensify customer satisfaction. To explain this acceptance, it also intended to provide to clarify the linkages between Six Sigma and customer satisfaction.

The outcomes of this study are going to provide a DMAIC method of Six Sigma adoption in the production context, which is going to be positioned as a basis for further development of a practical Six Sigma project evaluation framework.

To address this study question, five specific research objectives were outlined as follows:

- To identify gaps from the literature, to establish where it is necessary to augment the theoretical foundations of Six Sigma adoption in the production industry context.
- To explore how Production Company currently conduct Six Sigma projects and interpret their impact on improving the quality of customer service.
- To conceptualize, refine, and validate theory elements to be considered in understanding the linkages between Six Sigma and customer satisfaction.
- To develop a DMAIC method to explain Six Sigma in the rubber producer company and in particular to:
 - identify the linkages between Six Sigma and customer satisfaction and
 - provide the basis for a project evaluation framework.

- To suggest a potential Six Sigma project evaluation framework for assessing Six Sigma projects in the company.

Considering the research scope and objectives; case study will be used as the primary research strategy. The investigation design is additionally described in Chapter 3.

In this thesis, a literature review about Six Sigma has been made. In the phases of DMAIC, statistical analyses such as MSA, ANOVA, SPC and multi response Taguchi design of experiment tools have been used.

1.4 Structure of the Thesis

This thesis is organized in four chapter, as follows:

- Chapter 1 provides an overview of the research including: introduction, Six Sigma overview, research aims and objectives.
- Chapter 2 Six Sigma methodologies are examined in detail.
- Chapter 3 the current state and the importance of the problem have been investigated and DMAIC methodology has been implemented step by step for reducing the number of non-conformance for produced parts in Six Sigma project.
- Chapter 4 discusses the findings of this research and the contribution to knowledge. The limitations are indicated, leading to suggestions for future research.

CHAPTER TWO

SIX SIGMA

2.1 Introduction

The research background was briefly defined in the second chapter by emphasizing the importance of Six Sigma methodology. This provides an opportunity for researchers to enhance and improve the understanding of this phenomenon, especially in the production sector, becoming increasingly important in many industries.

In this chapter is going to review the relevant literature to provide the theoretical basis of the research. Nine main areas of literature are considered: Introduction, Six Sigma approach, the history of Six Sigma, The Benefits of Six Sigma, Six Sigma team roles, DMAIC methodologies, success factors for Six Sigma projects, statistical theory of Six Sigma, and 1.5σ shift. Consequently, the initial conceptual framework is founded to provide the research focalize.

2.2 Six Sigma Approach

Despite being brought forward by integrating statistics into quality philosophy by Motorola in 1985 (Basu & Wright, 2003), Six Sigma methodology has a century long history and background in its wake. The Six Sigma concept is not a newly created methodology at all, but rather based on the works of Shewhart, Deming, Juran, Ishikawa, Taguchi and other quality gurus, is brought together from quality programs in the past, defining the “quality” as the %99.73 of products, services or any other characteristics being in compliance with the required specifications. The companies, which apply Six Sigma, have determined the defect rate of a product, service or any other characteristic to be less than 3.4 in a million in order to achieve better results regarding the overall quality level (Black & Revere, 2006; Smith, 2001).

While many companies believed that it was too costly to produce high-quality products up until the 1980s, Motorola argued that “better is cheaper”. In this context,

Six Sigma methodology was brought forward by advocating that producing high-quality products reduces the costs and increased customer satisfaction raises the profitability. Six Sigma aims to increase the client satisfaction, to improve the effectiveness, efficiency, and profitability as a management strategy covering the whole range from the lowermost to the top level (Taghizadegan, 2006). The Six Sigma approach combines good quality that satisfies customers and an excellent return on investment that satisfies shareholders (Savolainen & Haikonen, 2007). Six Sigma is one of the most suitable ways to manage a process since it prioritizes the customer and uses incidents and data for the best solution (Pande & Holpp, 2001).

Six Sigma was designed, building upon statistical thinking and approaches with a particular focus on eliminating the variation in processes (Hensley & Dobie, 2005). Improvement in effectiveness and efficiency constitutes the main core of the Six Sigma concept (Ecks, 2001). Six Sigma is considered a methodology that makes tools for the improvement of the process capabilities available for all businesses (Yang & El-Haik, 2009).

Six Sigma's purpose is to detect and eliminate the sources of variation (McCarty, Bremer, Daniels & Gupta, 2004). Six Sigma improves the process rather than the product itself. Since each process and product is subject to the effects of the variables, Six Sigma seeks to reduce the variability and place it under control. The statistical term "Sigma or σ " is used to measure the variability of a process or a product (Brussee, 2004). Sigma, σ , represents the variance of the normal density distribution (Breyfogle, 1999; Pande & Holpp, 2002).

The structure of a Six Sigma process that is to take into account that if the process is centered at the target and the nearest specification limit is six standard deviations from the mean, the process will operate at the 3.4 million parts per million (ppm) defective level (Montgomery, 2010).

Six Sigma is not just a statistical method to measure the variance of the process/product; it is a process and culture to achieve operational excellence (Basu &

Wright, 2003). “Six Sigma initiatives are planned and implemented in organizations on ‘Project by Project’ basis. Each project aims not only to improve a chosen performance metric but also sustain the improvement achieved” (Subramaniam, Srinivasan & Prabakaran, 2011, p. 166).

Despite mostly being used to improve the manufacturing process in the past, the Six Sigma approach is being increasingly applied in other branches as well (Does, Heuvel, Mast & Bisgaard, 2002). Six Sigma’s applications contain Product and Process Design, Manufacturing Process, Business and Transactions for achieving quality levels of Six Sigma (Chowdhury, 2001). Also, it is known that the Six Sigma is also widely utilized in the health sector which is sharply less tolerant for the defects. R&D within the health sector, nuclear facilities, maintenance, repair, and overhaul, as well as military applications, stand out as other areas of use for Six Sigma.

2.3 The History of Six Sigma

From a classical point of view, the control on a finished product which is based on experience was adopted as the quality approach for many years. Following the World War II, the Japanese started to use scientific methods for the first time to increase the quality of the products. Joseph Deming, the American statistician, made an enormous contribution to this process. The 1980s witnessed struggles to improve procedures, affecting the industrial countries and various approaches were employed. However, the experience acquired as a result showed that one of the most suitable methods was a method based on the scientific data analysis called Six Sigma (Eckes, 2005).

Numerous supporters of Six Sigma consider it a natural advancement of TQM, asserting that Six Sigma can rely on the available TQM culture to bring about concrete results (McAdam & Lafferty, 2004). The world keeps changing is ongoing like before. Hence, quality management will always be in need of improvement and adaptation in the face of ever-changing conditions. In this way, industry constantly needs to experiment with new ideas Six Sigma was a big leap forward in comparison to the preceding quality management concepts. The TQM movement of the 1980s, including

the approaches of Genichi Taguchi, Deming, Kaoru Ishikawa and Juran was distinguished by a focus on quality improvement. This was an important switch from the predominant spotlight on inspection and quality control during the 1960s. Alterations in the environment also reinforces the developmental process (Bisgaard & De Mast, 2006).

Quality has always been an essential aspect of basically all products and services. However, acceptance of its relevance by the industry from a business perspective and the inauguration of an authoritative approach for quality control and improvement have been an evolutionary advancement (Montgomery, 2010).

The period from the point where the quality depended on the skills of the craftsman up until to the emergence of the Six Sigma methodology is elucidated below (Montgomery, 2009):

- 1700-1900: Quality depended on the skills of the craftsmen. Eli Whitney designed standard interchangeable parts to vulgarize the assemblage.
- 1875: Frederick W. Taylor, sectionalized the process to manufacture complex products by using scientific management principles. Frank Gilbreth and Henry Gantt made contributions later.
- 1901: First standardization laboratories were established in the United Kingdom. UK government created a supplier certification program.
- The 1920s: AT&T created the first quality department. Fisher published his works on experiment design in agricultural sciences. Shewhart used control charts for the first time. Dodge & Roming developed acceptance sampling plans.
- The 1930s: W.A. Shewhart, started giving lectures at the University of London on control charts and statistical methods in production. British and German companies began to employ design experiment. The Royal Statistical Society established the industrial and agricultural research department.
- The 1940s: Military sampling plans were published to utilize control charts for the process data analysis. Dr. Deming traveled to Japan and quality-consciousness took root. Prof. Dr. Taguchi began working on experiment design. International Standardization Organization was established.

- The 1950s: Cause and effect diagram of Prof. Ishikawa was used for the first time. The concept of Total Quality Control, CUSUM and EWMA control charts emerged. Industrial Quality Control publications started. Joseph M. Juran was invited to give lectures on Quality Management and Improvement. The Quality Control Handbook published by Juran and F. M. Gryna.
- The 1960s: Zero Defects program started. The concept of Quality Control Circle emerged. National Quality and Manufacturing Council was established in the UK as part of the British Manufacturing Council.
- The 1970s: National and international institutions were established increasing the importance of the quality globally, and developments took place for the experiment design in quality.
- The 1980s: The experiment design works of Prof. Taguchi were applied in the US. First quality system standards of the ISO were published. Malcolm Baldrige National Quality Award was rewarded by the US Congress. Quality Engineering Journal was published for the first time.
- The 1990s: The interest in ISO 9000 documents increased and companies started to adopt own procedures to improve quality. Six Sigma approach of Motorola begun to spread into other industries.
- The 2000s: Quality improvement activities expanded from traditional industrial branches into other sectors such as health, insurance, finance and public services.

Six Sigma has evolved following the emergence at Motorola and started to be adopted and used by many other companies. The chronological development and expansion phases of Six Sigma are as follows (Allen, 2006):

- Six Sigma Academy was established at Motorola in the 1980s.
- In 1992, Allied Signal created an infrastructure within the company for Six Sigma Academy techniques and started to establish positions according to the Six Sigma training levels. Many companies, including Texas Instruments and ABB adopted and adapted the training methods of Six Sigma Academy.
- During first years of the 1990s, multiple formal methods were published in order to improve the product and processes. These methods are Total Quality Development, Taguchi Methods, the decision analysis-based framework, and the

so-called “Six Sigma” methodology. All of these published practices and advancements seek to enable people concerned with system enhancement to utilize the methods to design their work even if they do not fully comprehend the incentives behind them.

- In 1995, General Electric (GE) signed an agreement with the Six Sigma Academy to develop its own training program. Since the GE is one of the most popular, leading companies in the world, this occasion is especially important for the expansion of Six Sigma. Jack Welch, the CEO, pushed the employees of all levels to take part in the Six Sigma problem-solving approaches. The approach of GE was to select black belt candidates among the personnel believed to be the leader of the future.
- In 1999, GE provided training to its suppliers and other business partners and started to compete with the Six Sigma Academy.
- In 2000, the American Society for Quality started with the black belt accreditations. Training in a classroom environment, completion of a test and signed protocols proving the successful implementation of Six Sigma projects were among the conditions to acquire the accreditation.

Bisgaard & De Mast (2006), conducted a predictive research with their publication “After Six Sigma-What’s Next?”. The current version of Six Sigma adopted most of the Juran’s approaches. It is also predicted for the future that a problem-solving approach with a scientific base will serve as the foundation for the professional business world. Six Sigma professional should be well trained and experienced in innovative skills related with Six Sigma.

Yusr, Othman & Mokhtar (2011) considered the connection between the creative management skills and Six Sigma as one of the organizational fields within the core foundation of quality.

The Six Sigma is a process-oriented program, and purposes to improve the process or product through the systematic approach (Mishra & Sharma, 2014). Therefore, it has been experiencing a rapid expansion throughout the industry and academy since

the beginning of the new millennium. This condition was examined by Bratic (2011) in this work “Six Sigma: A Key for Process Improvement”. In this project, the usage ratio of Six Sigma was compared with other quality improvement methods, and results are given in Table 2.1.

Table 2.1 Rating of process improvement techniques (Bratic, 2011)

PROCESS IMPROVEMENT TECHNIQUE	AFFECT RATIO (%)
Six Sigma	53.00
Process Mapping	35.20
Root Cause Analyze	33.50
Cause Effect Analyze	31.30
ISO 9001	21.00
Statistical Process Control	20.10
Total Quality Management	10.30
Malcolm Baldrige Criteria	9.80
Information Management	5.80

The increasing interest in Six Sigma attracted the attention of the academy. This condition was analyzed in the publication of Brady & Allen (2006). While 69.2% of the authors were in connection with the ten industrial branch and 30.8% in connection with the academy prior to 2003, the rate of the authors in connection with the academy increased up to 53% in 2003. As a result of this inclination, authors of academy origin constitute now the majority.

For the academic field of quality Six Sigma has become one of the most prominent trends in the past few years (Gerger & Firuzan, 2016).

The professional and academic management and engineering media have been paying focusing on Six Sigma in a growing manner (Bendell, 2006). Today, Six Sigma has already become a powerful approach for enhancing business efficiency in numerous prominent institutions by upgrading quality, decreasing costs and adding up value for the enterprise and customers (Antony, 2012).

In tandem with the advancements of the industrial age, the area of application for the Six Sigma continues to expand. Mechanical systems using water and steam power characterized the first phase of the industrial age, followed by the second phase characterized by assembly lines and use of electricity. Computing and automation initiated the third phase, and finally, the cyber-physical systems opened the fourth phase of the industrial age. The term "Industry 4.0" was coined in 2011 at the Hannover Fair. Through the incentives of the Federal Government of Germany, Industry 4.0 took its place in the modern industry. Industry 4.0 may be roughly described as innovation projects including, the robots taking over production completely, the development of artificial intelligence, the shift of production from factories to homes via 3D printers, the analysis and evaluation of vast amounts of information through data analysis methods, etc (Özel, 2017). Up until today, Six Sigma applications were conducted in the third phase (computing and automation) of the industrial age. However, changes and improvements on Six Sigma applications will be inevitable following the fourth step taking root. Therefore, the usage of Six Sigma will adapt to these innovations and keep on spreading.

2.4 The Benefits of Six Sigma

The Six Sigma approach has proven to be extremely effective at saving cost and increasing customer satisfaction.

Six Sigma methodology focuses on the dominant root causes and ensures the intended outcomes, both in terms of enhancements desired and time span fixed. It is a systematical, data-driven concept and technique for discarding defects in any kind of process from manufacturing to transactional and from products to services. This pioneering enhancement technique provides results of productivity, profitability and quality improvements based on its utterly efficient approach (Desai, 2008).

Six Sigma is a systematic, extremely disciplined, customer-oriented and profit driven organization-wide strategic business enhancement initiative that takes root in a

data driven methodology focusing on an accurate process (Tang, Goh, Lam & Zhang, 2007).

It drives client satisfaction and bottom-line results by systematically reducing variation in processes and thereby promoting a competitive advantage (Antony & Desai, 2009).

Pande, Neuman & Cavanagh (2003) summarized the benefits of Six Sigma as follows:

- **Leads to permanent success:** Six Sigma creates a culture providing constant improvement and makes the success a sustainable result.
- **Sets a performance goal for everyone:** Performance may only be improved, when it can be measured. Each individual, unit or department may have differing expectations and goals. However, offering products, services or information to the customer is the mutual objective for everyone.
- **Increases the value offered to the customer:** The focus underlying the Six Sigma approach is to the customer. It includes finding out what the concept of value means for the customers and potential customers and planning how to offer the value to the customers in the most suitable way.
- **Increases the improvement rate:** Thanks to many tools and ideas borrowed from many other disciplines, Six Sigma improves not only the performance of a company but also the improvement rate itself.
- **Supports learning and the dissemination of information:** Six Sigma is an approach providing for the company-wide dissemination of ideas and accelerates thought sharing.
- **Implements strategic changes:** Tasks such as offering new products, taking new risks, entering new markets, acquisition of new companies has now become daily procedures for many companies.

Snee (2010), gathers the benefits of Six Sigma under two different categories, as human-related and process-related aspects. This classification is shown in Table 2.2.

Table 2.2 Human and process aspects of improvement

Human related aspects	Process related aspects
Focusing on results	Process improvement
Management leadership	Variation analysis
Sens of attachment	Disciplined approach
Focusing on customer	Quantitative measurements
Project teams	Statistical ideas and methods
Cultural change	Process management

As Sanders & Hild (2000) says “One of the distinct advantages of the Six Sigma Engineering strategy is the similar educational and technical backgrounds of the individuals undergoing the training. The common quantitative background allows more mathematical and technical tools to be taught at a faster pace” (p. 305).

In comparison with other quality initiatives, the primary difference of Six Sigma is that it not only applicable to the product quality but also to all features of a business operation by boosting fundamental processes (Yang & El-Haik, 2009).

2.5 Six Sigma Team Roles

Six Sigma is a team-oriented approach for problem-solving and process enhancement. In the pursuit of improved operational efficiency and greater customer satisfaction, Six Sigma has been accepted as a systematic and structured procedure that seeks to improve the process capability by concentrating on customer requirements (Dasgupta, 2003; Harry, 1998).

Despite Six Sigma projects covering the whole company or an individual process, a team is created and tasked to achieve goals. A well-organized team will obtain better and faster results. Roles and responsibilities of these roles within a Six Sigma project are shown in Figure 2.1.



Figure 2.1 Performance improvement roles (George, 2002)

Sponsors determine goals by creating a vision. They are positioned at the upper management level of the companies. These positions include company owner, CEO, general manager, executive board member, etc. The sponsor primarily creates the road map to be followed for Six Sigma application and ensures that the whole organization acts in accordance with this road map (Polat, Cömert & Arıtürk, 2005).

Champions take part directly in the projects at a company (Ho, Chang & Wang, 2008). While sponsors participate only part time, champions attend the projects full time. In line with the authorization acquired from the sponsor, champions are responsible for the availability of the required work force and financial resources, as

well as the coordination. Champions are in charge for the selection of the projects and the determination of objectives. In the project phase, they are responsible for the success of the project by providing the data and other necessities which Six Sigma team requires (Öztürk, 2009). Champions usually receive a multiple-day training in order to comprehend the Six Sigma terminology and the new roles (Sleeper, 2006).

Master Black belts are the experts with the scientific background knowledge required to determine where and how the statistical and non-statistical methods are to be used. They possess the utmost technical and administrative knowledge. Master black belts take part in the projects part time, and they are responsible for the training of the sponsors, champions, black belts, green and yellow belts at the company. They also act as coaches and instructors for the project leader black/green belts. Master black belts usually take part in two-year periods (Stamatis, 2003).

Black belts are selected by champions in accordance with their leadership, communication skills, and technical knowledge. Black belts employing the DMAIC problem-solving method usually receive a four-week training. The contents of the training cover the statistical and non-statistical tools required for the DMAIC process (Sleeper, 2006). Since black belts are representatives and leaders of the change process, they fulfill a crucial role in minimizing the resistance to be experienced during the cultural adaptation. The number of black belts at a company is relative, for Coronado & Anthony (2002) a black belt for each 50 – 100 employees is required.

Since green belts participate as only part-time problem solvers, they continue to fulfill previous duties in contrast with the black belts. Green belts are responsible for the following tasks (Levine, 2006):

- preparation of the project announcement,
- review of the project announcement with the champion,
- selection of the project members,
- as the process owner, communication with the black belt, master black belt and champion in all phases of the project,
- providing assistance to the team in all phases of the project,

- planning and coordination of meetings,
- analysis of the data in all phases of the project
- training the team members on basic tools and methods in all phases of the project.

For Coronado and Antony (2002), a green belt for each 20 employees is required. This ratio clearly shows how important the training of the green belts is for the company.

Yellow belts are the employees ensuring the information flow needed by the project leaders; they are selected in accordance with their technical specialties (Eckes, 2001).

2.6 DMAIC Methodology

Six Sigma is a systematic methodology aimed at operational excellence through continuous process improvements (Zhang, Wang, Goh & He, 2015). The Six Sigma methodology consists of five interconnected phase. These are define, measure, analyze, improve and control (DMAIC). At the heart of the Six Sigma problem-solving methodology is DMAIC. The Six Sigma tools are mostly used within the DMAIC framework (Cabrita, Domingues & Requeijo, 2016). The detailed composition and progression of DMAIC tools utilization could diverge from one organization to another and from project to project. However, their application and logical flow is what facilitates the total impact of Six Sigma (Goh, 2002).

The DMAIC method is generally used when an existing product or process is inadequate. DMAIC focuses on the elimination of inefficient business processes, the application and development of new metrics and the use of technology to ensure improvement (Jones, Parast & Adams, 2010).

Companies preferring the Six Sigma DMAIC methodology utilize this method in order to achieve real improvements and results (Park, 2003).

DMAIC provides a roadmap for the Six Sigma team. The DMAIC roadmap provides a problem-solving process that does not exist before (Sleeper, 2006). This approach allows structural flexibility (McCarty et al., 2004). DMAIC provides a road map and makes an innovative problem-solving process available for the Six Sigma team. This approach allows structural flexibility as well.

Six Sigma DMAIC method focuses on a specific area of interest. However, Six Sigma projects with a large scope may concentrate more than one areas, and it may take three to eight months to complete these projects (Lynch, Bertelino & Cloutier, 2003).

Problem and customer requirements are defined in the definition phase (Henderson & Evans, 2000). Main goals of this phase are as follows (Stamatis, 2003):

- identification of the problem,
- identification of the customer,
- determination of critical quality characteristics,
- process map creation, and
- update the project scope and plan, if necessary.

Problem definition does not only focus on the output or the finished product but at the same time on the process of generating the product or the service itself (Chowdhury, 2001). “The top management shall identify the problem according to customer feedback, strategy and mission of company, define customer requirements, and set goal” (Hung & Sung, 2011, p. 581).

Potential causes of the problem are defined in the measurement phase by using various statistical tools (Sleeper, 2006). In line with the goals defined in the previous phase, accurate and realistic indicators are determined in order to facilitate the surveillance of the developments (Pyzdek, 2003). The measurement system (Gage R&R) is verified in this phase (Prashar, 2016). SS team collects the up-to-date data required for the measurement phase of DMAIC (McCarty et al., 2004). Measurement phase includes following activities (Stamatis, 2003):

- defining the measurement and variance,

- determining the data type,
- developing a data collection plan,
- performance measurement system analysis,
- management of data collection,
- conducting graphical analyses, and
- conducting basic analyses.

Analysis phase focuses on the analysis of the product/process metrics and their comparison. Basic quality control tools and various statistical techniques are used for the analysis of product/process performance (Park, 2003). Root causes of the problems in the process are determined. Six Sigma team employs various statistical tool and techniques in order to single out the root cause (McCarty et al., 2004).

Metrics and their comparison. Basic quality control tools and various statistical techniques are used for the analysis of product/process performance (Park, 2003). Root causes of the problems in the process are determined. Six Sigma team employs various statistical tool and techniques in order to single out the root cause (McCarty et al., 2004).

Critical analyzes at this phase are done with the help of some auxiliary tools such as Ishikawa and Pareto analysis. Ishikawa diagrams are used to describe and systematically list the root causes of a problem. These diagrams also allow the appraiser to determine which of the various root causes has the most effect. To reduce of many root causes, Pareto diagrams are used. Pareto diagrams help us that quickly identify and manage critical areas (Prasad, Subbaiah & Padmavathi, 2012, p. 227).

The improvement phase aims to take the causes found in the analysis phase into account, and also to choose and target solutions to eradicate such causes (Antony, 2005). Chen & Brahma (2014) figure out that the improvement phase is the beginning of the statistical analysis. This step statistically examines the differences in the process and determines which factors contribute significantly to the output.

Statistical methods are also used to verify improvement (Pyzdek, 2003). Control phase seeks to implement continuous measures and actions to preserve the improvement by tracking, standardizing, documenting and integrating the new process on a daily basis (Pande, Neuman & Canavagh, 2000). The aim of the control phase is to enforce the accepted solution and ensure that the gains acquired from the enhancement are maintained (Hsieh, Lin & Manduca, 2007). Control phase includes following (Stamatis, 2003):

1. Poka-yoke method,
2. Development of long term “measurement system analysis”,
3. Control chart applications,
4. Development of a reaction plan,
5. Updating standard work and training programs.

2.7 Success Factors for Six Sigma Projects

Spectacular success stories of Six Sigma projects and constantly increasing global interest induced many companies to eagerly apply the Six Sigma methodology (Firuzan, Alpaykut & Gerger, 2012). Six Sigma project objectives must be: clear, succinct, specific, achievable, realistic and measurable (Gerger & Firuzan, 2012).

Michael L. George (2002) states, “*I’ve never witnessed a failed Six Sigma project with the interest and support of the upper management, however, I’ve never seen a successful Six Sigma project without this interest and support either*”. For George (2002); there are nine team roles present for the success of the projects. These roles and responsibilities are given in Table 2.3.

Table 2.3 Nine Team Roles (George, 2002)

<i>Role</i>	<i>Team-Role Contribution</i>	<i>Allowable Weaknesses</i>
Thinking Team Roles		
Plant (creative)	Creative, imaginative, unorthodox. Solves difficult problems.	Ignores details. Too preoccupied to communicate effectively.
Monitor Evaluator (objective)	Sober, strategic and discerning. Sees all options. Judges accurately.	Lacks drive and ability to inspire others. Extremely critical.
Specialist (knowledgeable)	Single-minded, self-starting, dedicated. Provides knowledge and skills in rare supply.	Contributes only a narrow front. Dwells on technicalities. Overlooks the “big picture.”
Doing Team Roles		
Shaper (hard driving)	Challenging, dynamic, thrives on pressure. Has the drive and courage to overcome obstacles.	Can provoke others. Hurts people’s feelings.
Implementer (organizing)	Disciplined, reliable, conservative and efficient. Turns ideas into practical actions.	Somewhat inflexible. Slow to respond to new possibilities.
Completer (meticulous)	Painstaking, conscientious, anxious. Searches out defects and omission. Delivers on time.	Inclined to worry unduly. Reluctant to delegate. Can be a nit-pickier.
Personnel Team Roles		
Team Worker (diplomatic)	Cooperative, mild, perceptive and diplomatic. Listens, builds, averts friction, and calms the waters.	Indecisive in crunch situations. Can be easily influenced.
Resource Investigator (outgoing)	Extrovert, enthusiastic, communicative. Explores opportunities. Develops contacts.	Overoptimistic. Loses interest once initial enthusiasm has passed.
Coordinator (motivator)	Mature, confident, a good chairperson. Clarifies goals, promotes decision-making, delegates well.	Can be seen a manipulative. Delegates’ personal work.
<p><i>Strength of contribution in any one of the roles is commonly associated with particular weaknesses. These are called allowable weaknesses. Executives Managers and indeed everyone are seldom strong in all nine team roles.</i></p>		

The success of SS projects is generally expressed in terms of financial gains. Various indicators such as increase in customer satisfaction, decrease in number of

complaints and reduction in rate of defective products besides financial gains are also used to measure the success of the projects (Kuvvetli, Firuzan, Alpaykut & Gerger, 2016).

There are many studies about the factors that affect the success levels of Six Sigma projects in the literature. While some of these studies include the analysis of the situation in their own countries, other studies are approaching more extensively (Zu, Robins & Fredendall, 2010).

Due to the robust statistical techniques contained in the Six Sigma projects, training and infrastructure are among the utmost important factors. If a company does not utilize the Six Sigma methods correctly, the project is likely to fail, and this will cause the belief that the statistical techniques are ineffective (Breyfogle, 1999). In such cases, the company will either refrain from applying Six Sigma or distance itself from the Six Sigma logic.

DMAIC method shall incorporate following points for Six Sigma projects to succeed: (Lynch et al., 2003):

- **Problem:** Project shall focus on a problem without a readily available solution in the organization.
- **Goals:** The goals of the project shall be clearly defined in a quantitative aspect.
- **Project surveillance:** Progress metrics shall be monitored.
- **Benefits:** Project costs, timing and quality increase shall result in a measurable advantage.
- **Application calendar:** Project is required to be implemented in a certain period of time, it takes usually three to six months.
- **Process:** Project shall follow the DMAIC process to resolve the problem.
- **Tools:** Six Sigma tools shall be utilized in line with the DMAIC methodology.
- **Skill and confidence level:** Projects shall increase the self-confidence of the black belt and the project team itself by utilizing the DMAIC methodology. Successful Six Sigma results increases the organizational confidence at the same time as well.

- **Process orientation:** Projects are subject to a process improvement orientation.

Six Sigma work strategies should provide correct metrics for every position. The choice of a process improvement method depends on the culture of the institution involved. More and more organizations are trying to determine which improvement method will work best and which will best suit their culture (Nave, 2002). As a rule, the project selection must be based on a translation of the company strategy into operational goals (Koning, Verver, Heuvel, Bisgaard & Does, 2006).

Many works are available in the literature, proving the success of the Six Sigma projects. The contents of these works vary in accordance with the culture, geographical area, and the industry. In fact, it is common to encounter enormous differences on a project basis. Considered as out of scope, these works are not mentioned in this thesis.

2.8 Statistical Theory of Six Sigma

According to Sanders & Hill (2000), “the 6σ methods are based heavily on the use of statistical methods to understand the product and process performance” (p. 303).

According to Park (2003), the data values for any process or product characteristic vary at all times. No two products or characteristics are absolutely identical as each process contains numerous causes for variability. The dissimilarities among products may be great, or unmeasurably small, but they always exist. Variation is the essential feature of the process performance. There are numerous origins of variation for process and product characteristics. It is common to group those under two categories: common causes and special causes. Common causes refer to the variation sources within a process that exhibit a stable and repeatable distribution over time. This is called ‘in a state of statistical control’. The random variation, which is deep-rooted in the process, is not effortlessly removable unless we alter the sheer design of the process or product, and is an omnipresent common cause. Common causes act like a stable system of incidental causes. If solely common causes of variation exist and do not deviate, the output of a process is foreseeable.

The common cause's variation is noise factor in the system. The system is under control when the common cause variation is seen.

Processes with this type of variables are considered stable operations (Sleeper, 2006). It is shown as a graphic in Figure 2.2.

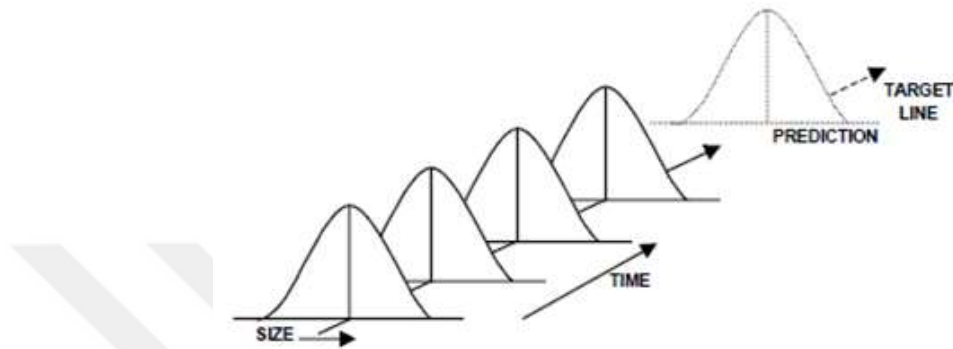


Figure 2.2 Variation: Common causes (Park, 2003)

If only common causes of variation are present, the output of a process forms a distribution that is predictably stable over time (Lean Academy, 2012).

As pointed out by Park (2003), special causes refer to any factors generating variation that are normally not contained within the process. That is, when they appear, they cause an alteration in the process distribution. Unless all the special causes of variation are diagnosed and handled, they will keep on influencing the process output in erratic ways. If special causes exist, the process output is not stable over time.

Considering its past, quality management was concerned with detecting and removing the special causes of variation. It is shown in Figure 2.3.

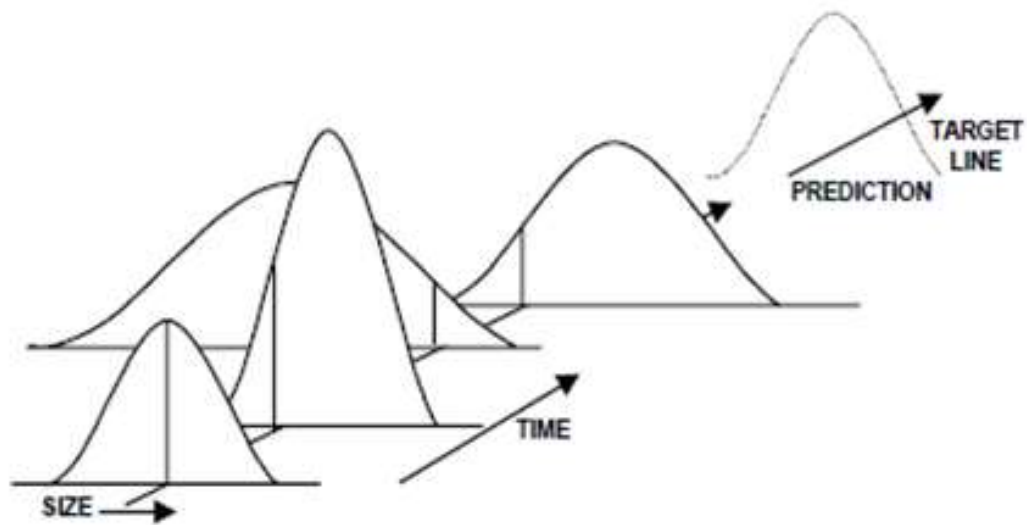


Figure 2.3 Variation: Special causes (Park, 2003)

If special cause of variation is present, the process output is not stable over time. Special Cause Variation is due to differences between people, machines, materials, methods, etc. The occurrence of a special cause results in an out of control condition.

Many statistical tools assume that the data distribute normally. Key properties of a normal distribution are as follows (McCarty et al., 2004):

- There is a peak point.
- Data are distributed symmetrically to both sides.
- Tails theoretically lead to negative and positive infinity.
- Areas on both sides below the curve are equal to each other.

The normal distribution is the distribution where the average is zero, and the standard deviation is one. The normal distribution is the most important probability distribution used both in the statistics application and theory. If x is a random variable, a probability distribution of x is defined as follows (Montgomery, 2009):

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}, -\infty < x < \infty \quad (2.1)$$

$f(x)$, an ordinate height of the curve,

π , pi with a value of approximately 3.14159

e , the base of the natural logarithm with a value of approximately 2,71828

μ , the average of the mass exhibiting normal distribution

σ , the standard deviation of the normal distribution ($\sigma \geq 0$)

Here, π and e numbers are known mathematical constants, μ and σ are the parameters of the distribution.

Expected value of normal distribution:

$$\mu = np \quad (2.2)$$

Variance of normal distribution:

$$\sigma^2 = npq \quad (2.3)$$

The normal distribution is mainly used for the analysis of the distribution of the measurement defects and constitutes the backbone of the statistical theory with its many attributes. If certain conditions are fulfilled, many continuous and discrete variables draw near to the normal distribution.

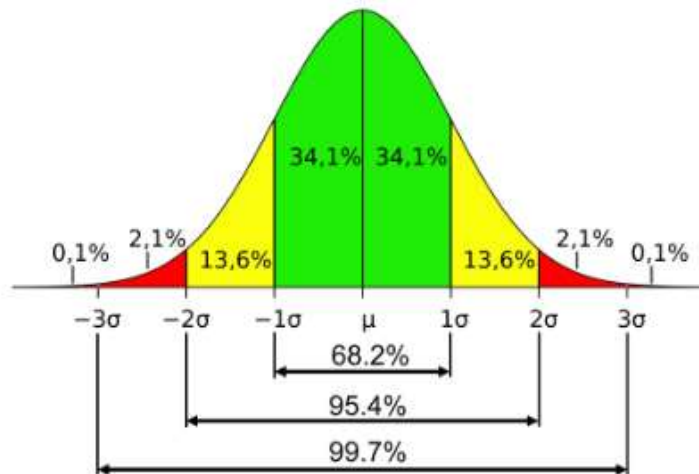


Figure 2.4 Segmented bell-shaped curve (Eckes, 2001)

“Total area under the normal distribution is 100%, which can be divided by the standard deviation” (Eckes, 2001, p. 35). 68.26% of the population is within $\pm 1\sigma$ of the μ . It has shown Figure 2.4.

Since the distribution is symmetrical Mod=Median=Arithmetical. Mean is equal to each other in normal distribution.

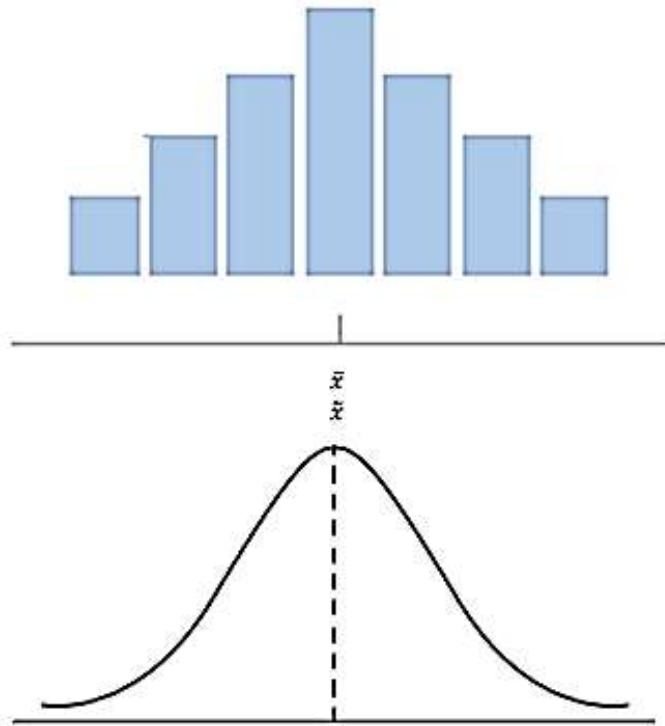


Figure 2.5 Normal distribution

Arithmetical mean = median: symmetry or zero Skewness

Normal distribution curve is symmetrical around the mean. Therefore the mean and the median of the distribution and the peak value x are on the same point on the axis.

In the normal probability distribution

$\mu \pm \sigma$ boundaries encompass %68.26 of the data,

$\mu \pm 2\sigma$ boundaries encompass %95.46 of the data,

$\mu \pm 3\sigma$ boundaries encompass %99.73 of the data.

In a similar manner,

%50 of the elements are positioned within $\mu \pm 0.574\sigma$ boundaries,

%90 of the elements are positioned within $\mu \pm 1.645\sigma$ boundaries,

%95 of the elements are positioned within $\mu \pm 1.960\sigma$ boundaries,

%99 of the elements are positioned within $\mu \pm 2.575\sigma$ boundaries.

In practice, the data may not always exhibit a normal distribution, i.e., symmetry. Distribution can be left-skewed or right-skewed. For the normal distribution, the

coefficient of Skewness is $\alpha_3 = 0$ and the coefficient of kurtosis is $\alpha_4 = 3$ (Panik, 2005).

Skewness shows the symmetrical irregularity and is calculated as follows:

$$\alpha_3 = \frac{E(x-\mu)^3}{\sigma^3} \quad (2.4)$$

Skewness to the left or negative Skewness shows that the majority of the data are above average, see Figure 2.6.

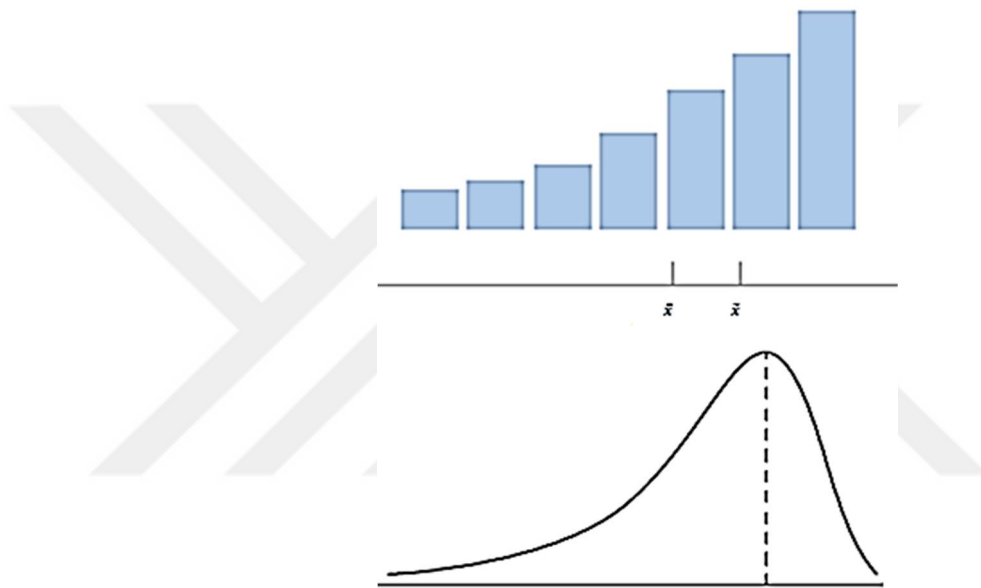


Figure 2.6 Left skewness or negative distribution

Mean < median: negative or left-skewed

Skewness to the right or positive Skewness shows that the majority of the data are outside the determined limit values, see Figure 2.7.

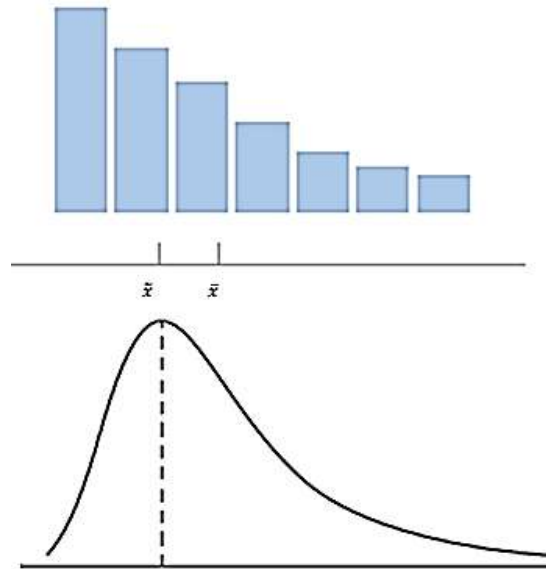


Figure 2.7 Right skewness or positive distribution

Arithmetical mean > median: positive or right-skewed distribution

Information on the symmetry or the Skewness of the distribution is obtained through the value of Skewness. There are three Skewness configurations listed below:

1. If $\alpha_3 = 0$, the distribution is symmetrical.
2. If $\alpha_3 < 0$, the distribution is left-skewed.
3. If $\alpha_3 > 0$, the distribution is right-skewed.

It is not sufficient only to have the Skewness value on hand in order to interpret the data. The kurtosis value shall be available as well equation (Panik, 2005). Kurtosis gives the “pointiness” of a distribution and is calculated through the following.

$$\alpha_4 = \frac{E(x-\mu)^4}{\sigma^4} \quad (2.5)$$

In a normal distribution, the kurtosis is equal 3.

1. If $k < 3$, negative kurtosis (platykurtic),
2. If $k = 3$, normal kurtosis (mesokurtic),
3. If $k > 3$, positive kurtosis (leptokurtic).

A “kurtosis” frequency curve may be in three forms (Kazmier, 2004).

- Flat (observations are equally spread among classes): **Platykurtic**
- Neither flat, nor pointy (regarding the distribution of observed values):
Mesokurtic
- Pointy (observations are concentrated in a narrow value range): **Leptokurtic**

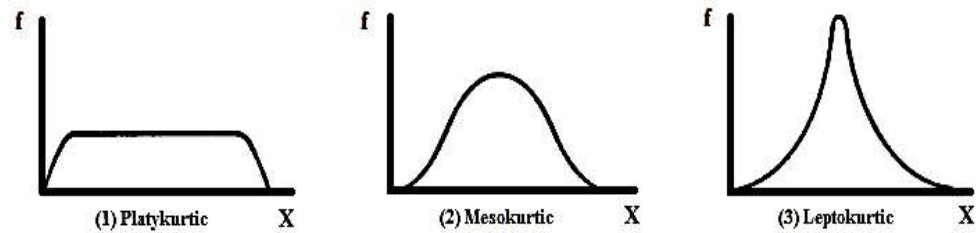


Figure 2.8 Kurtosis frequency types (Kazmier, 2004)

Process capability is explained as the ability of any product or service to meet customer expectations (McAdam & Lafferty, 2004).

A process capability index is a measure comparing the actual performance of a process with its specified performance, where processes are viewed as a combination of the factory or equipment, the very method itself, the people, the materials and the environment. The ultimate minimum requirement is that three process standard deviations on both sides of the process mean are restrained within the specification limits. This means that a 99.7 percent of the output will be within the tolerances. Process capability indices are simply a means of indicating the variability of a process relative to the product specification tolerance (Oakland, 2003).

Capability can be determined with several indices. There are the traditional methods defined by C_p and C_{pk} , and there are the sigma values corresponding to the part per million defects. Each of these methods uses specification limits as defined by the customer and can be defined as the USL – LSL (El-Haik & Roy, 2005).

Where USL and LSL are the process upper and lower specification levels.

\bar{x} chart

$$\text{Center Line} = \bar{\bar{x}} \quad (2.6)$$

$$UCL_{\bar{x}} = \bar{\bar{x}} + A_2\bar{R} \quad (2.7)$$

$$LCL_{\bar{x}} = \bar{\bar{x}} - A_2\bar{R} \quad (2.8)$$

R chart

$$\text{Center Line} = \bar{R} \quad (2.9)$$

$$UCL = D_4\bar{R} \quad (2.10)$$

$$LCL = D_3\bar{R} \quad (2.11)$$

“The \bar{x} and R control charts allow both ... and ... long-term process capability to be analyzed. It is particularly helpful if the data for a process capability study are collected in two to three different time periods” (Montgomery, 2009, p. 364).

C_p , a term used to define process capability, is mathematically expressed by:

$$C_p = \frac{\text{Specification width (design tolerance)}}{\text{Process capability (tolerance variation)}} \quad (2.12)$$

Specifically,

$$C_p = \frac{(USL - LSL)}{6\sigma \text{ (total process range from } -3\sigma \text{ to } +3\sigma)} \quad (2.13)$$

Where σ is:

$$\sigma = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n-1}} \quad (2.14)$$

This formula can be expressed conceptually as,

$$C_p = \frac{\text{(Product specification)}}{\text{Manufacturing variability}} \quad (2.15)$$

According to Joglekar (2003), the C_p index assumes the following four conditions:

1. The specification is two-sided.
2. The process is perfectly centered in the middle of the specification.
3. The process is stable.
4. The process is normally distributed.

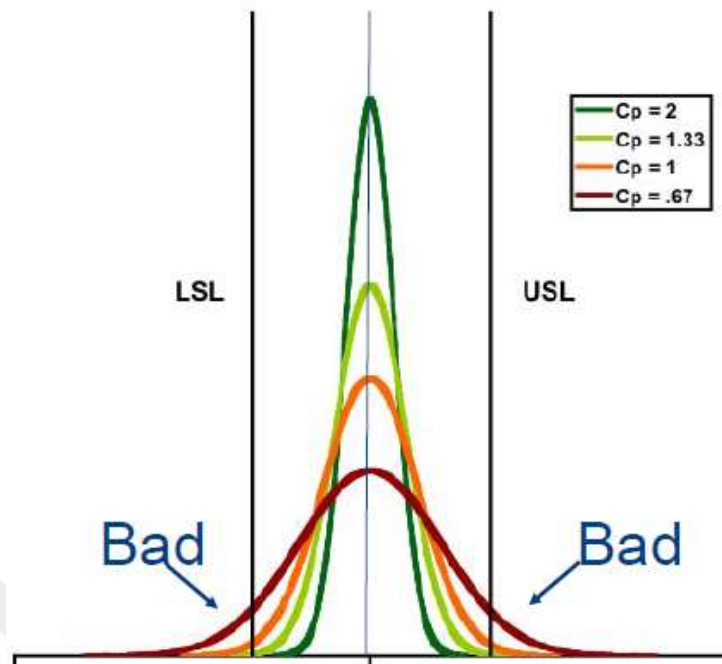


Figure 2.9 Various C_p levels

The Figure 2.9 shows centered distributions with various C_p levels. Note C_p levels less than two have visible tails outside the acceptable limits (Lean Academy, 2012). It has been shown of C_p levels capability in Table 2.4.

Table 2.4 C_p values (McCarty et al., 2004)

Value	Interpretation of C_p
$C_p < 1.0$	Poor capability
$1.0 \leq C_p \leq 1.5$	Marginal capability
$C_p > 1.5$	Good capability
$C_p > 2.0$	6σ capability

As figure out Park (2003), “when the spread is wide ... the C_p value is small, indicating a low process capability. When the spread is narrow ... the C_p value becomes larger, indicating better process capability” (p. 20).

As point out Joglekar (2003), “a higher C_p index means less nonconforming product.... The C_p index can be improved in two ways: by widening the specification and by reducing short-term variability” (p. 137).

A 3σ process, normally distributed, gives a C_p of 1.0 with 66,807 defective parts per million. In contrast, a six sigma process will give a rate of only 3.4 ppm outside the limits. The higher the sigma level, the less likely a process is to create defective parts (McAdam & Lafferty, 2004).

If the distribution is off center, the probability of a bad result drastically increases. In this case; C_{pk} is used. The equation for C_{pk} is:

$$C_{pk} = \min \left[\frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma} \right] \quad (2.16)$$

The C_{pk} levels are smaller than the corresponding C_p levels. This illustrates the need for both control variation and accurately hit the desired mean (Joglekar, 2003).

According to Joglekar (2003), “The C_{pk} index relaxes these two assumptions while retaining the following two assumptions” (p. 138):

1. The process is stable.
2. The process is normally distributed.

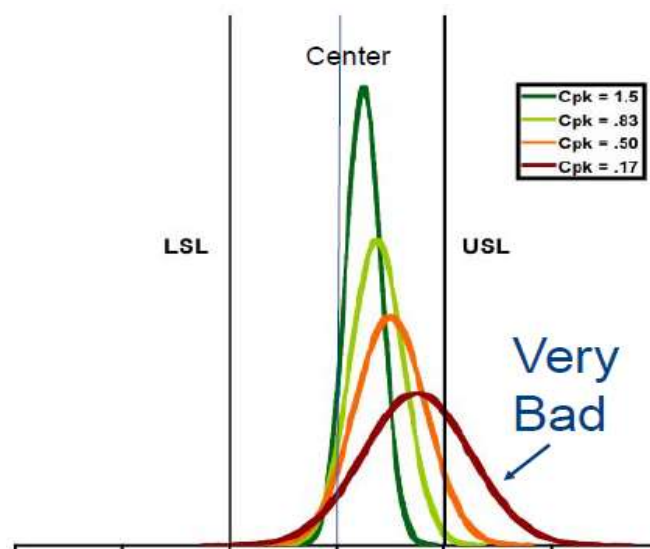


Figure 2.10 Various C_{pk} levels

It has been shown an interpretation of C_{P_k} levels capability in Table 2.5.

Table 2.5 C_{P_k} values (Oakland, 2003)

Value	Interpretation of C_p
$C_{P_k} < 1$	A situation in which the producer is not capable and there will inevitably be non-conforming output from the process.
$C_{P_k} = 1$	A situation in which the producer is not really capable, since any change within the process will result in some undetected non-conforming output.
$C_{P_k} = 1.33$	A still far from acceptable situation since non-conformance is not likely to be detected by the process control charts.
$C_{P_k} = 1.5$	Not yet satisfactory since non-conforming output will occur and the chances of detecting it are still not good enough.
$C_{P_k} = 1.67$	Promising, non-conforming output will occur but there is a very good chance that it will be detected.
$C_{P_k} = 2$	High level of confidence in the producer, provided that control charts are in regular use.

The C_{P_k} index can take values from $-\infty$ to $+\infty$. It is negative when the process means is outside the specification and may be improved in three ways: by widening the specification, by reducing the short-term variability, and by changing the process mean. When the mean is perfectly centered in a two-sided specification, C_{P_k} index becomes equal to the C_p index (Joglekar, 2003, p. 138).

Table 2.6 Setting capability goals (Joglekar, 2003)

Sigma Level	C_p	C_{pk}	Non-conforming PPM	% Conforming	Number of Characteristics for System Acceptance probability of:	
					99%	99.9%
3σ	1.00	0.50	66,800	93.32	0	0
4σ	1.33	0.83	6,210	99.379	1	0
5σ	1.67	1.17	233	99.9767	43	4
5.5σ	1.83	1.33	63	99.9937	159	15
6σ	2.00	1.50	3.4	99.99966	2,955	294

Defects per Million Opportunities is calculated with using the following sample formula (McCarty et al., 2004):

$$DPMO = \frac{\text{Defects} \times 10^6}{\text{Unit} \times \text{Opportunities}} \quad (2.17)$$

For example; the team took a sample of 250 bills and found 60 defects. The DPMO was (McCarty et al., 2004):

$$DPMO = \frac{60 \times 10^6}{250 \times 1} = 240,000$$

In the mean time Table 2.7 shows more details the relationship between process capability index and sigma level.

Table 2.7 Relationship between C_p and C_{pk} and Sigma level (Park, 2003)

C_p	C_{pk} (1.5 σ shift is allowed)	Quality Level
0.50	0.00	1.5 σ
0.67	0.17	2.0 σ
0.83	0.33	2.5 σ
1.00	0.50	3.0 σ
1.17	0.67	3.5 σ
1.33	0.83	4.0 σ
1.50	1.00	4.5 σ
1.67	1.17	5.0 σ
1.83	1.33	5.5 σ
2.00	1.50	6.0 σ

Six Sigma is achieved when the product specifications are at $\pm 6\sigma$ of the manufacturing process corresponding to $C_p = 2$ or $C_{pk} = 1.5$ (Park, 2003).

2.9 1.5 σ Shift

Six Sigma as a statistical measurement technique is a quantitative indicator of how “good” products, services and processes are and shows how much the process at hand deviates from the point of “zero defect” (Pyzdek, 2003). The amount of this deviation is measured by “sigma”. As an example, a company working at sigma performance level 1 experiences approximately 697,672 defects per million opportunities (DPMO). If the sigma performance level is 2, then the amount of defects will decrease down to 308,000 times. When it is considered that most of the companies operate at sigma performance levels of 3 and 4, this corresponds to a defect frequency of 66,800 and 6,210 respectively. A process operating at sigma quality level 6 will result in a 3.4 defective products or services in a million (Pande et al., 2000).

A defect rate of 3.4 in a million is used within Six Sigma definition, which is a higher value, instead of 2 in a billion. The reason is that the process average exhibits 1.5 σ shift in the long term.

After a process has been improved using the Six Sigma DMAIC methodology, appraiser calculates the process standard deviation and sigma value. These are considered to be short-term values. Because the data only contains common cause variation. DMAIC projects data occur over a period of months, rather than years. Otherwise, Long-term data contains common cause variation and special cause variation. Because short-term data does not contain this special cause variation, it will typically be of a higher process capability than the long-term data. This difference is the 1.5 sigma shift. Long-term sigma is determined by subtracting 1.5 sigma from our short-term sigma calculation to account for the process shift that is known to occur over time (www.isixsigma.com, 17.04.2017).

The process mean is required to be kept at the target value. However, due to various reasons, the process average changes from one-time period to another. This means that the process means continuously moves around the target value. To get the maximum shifts in the process mean, Motorola added a shift value of $\pm 1.5\sigma$ to the process average. This shift in the mean is used when calculating the sigma level of a process as shown in Figure 2.12. As seen from this figure, the 6σ quality level corresponds to 3.4 ppm. Table 2.8 shows how the ppm ratio changes when the sigma quality level changes (Park, 2003).

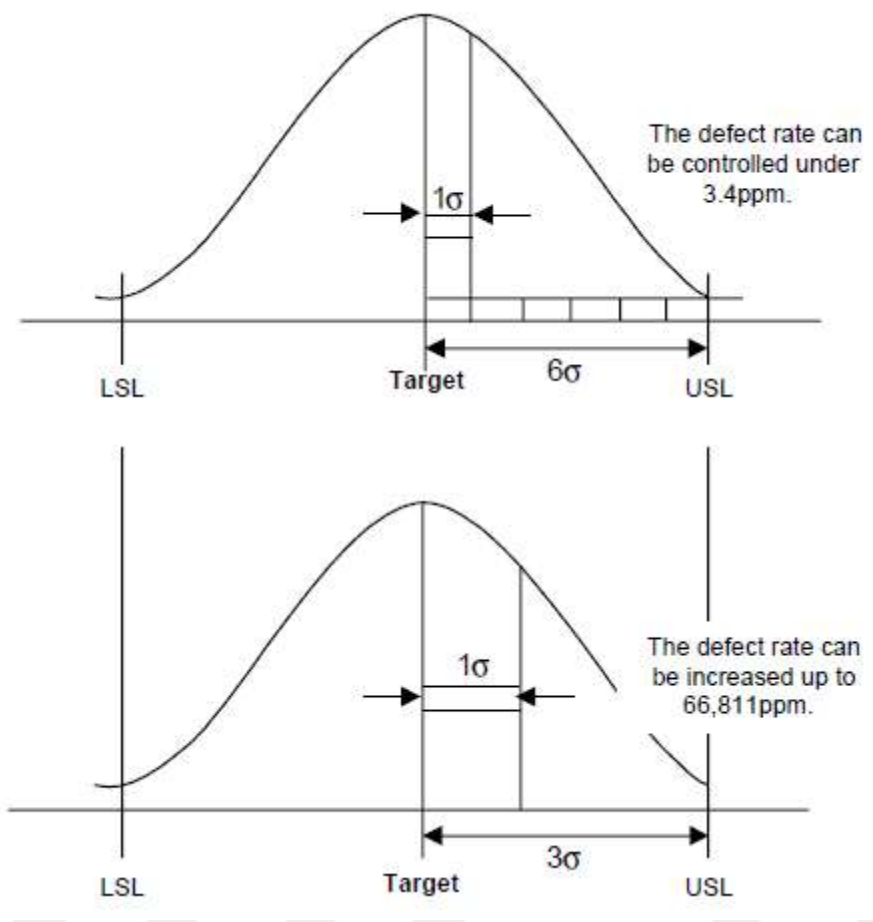


Figure 2.11 Sigma quality levels of 6σ and 3σ (Park, 2003)

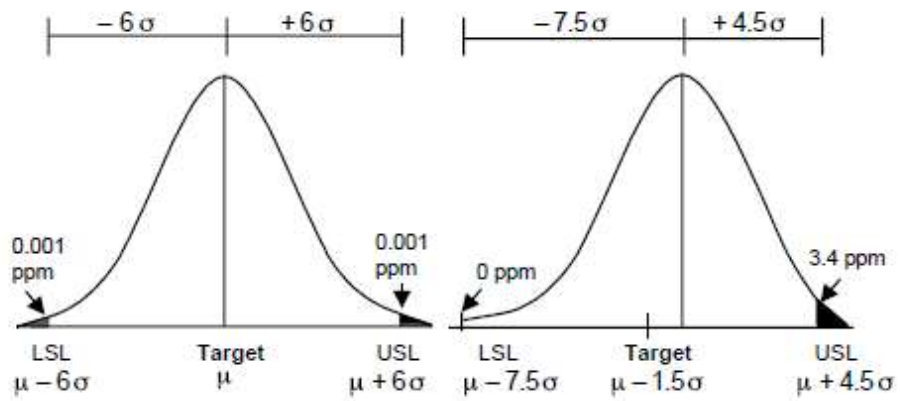


Figure 2.12 Impacts of a 1.5σ shift of process mean when the 6σ quality level is achieved (Park, 2003)

Table 2.8 PPM changes when sigma quality level changes (Park, 2003)

Sigma Quality Level	Process mean, fixed		Process mean, with 1.5 σ shift	
	Non-defect rate (%)	Defect rate (ppm)	Non-defect rate (%)	Defect rate (ppm)
1σ	68.26894	317,311	30.2328	697,672
2σ	95.44998	45,500	69.1230	308,770
3σ	99.73002	2,700	93.3189	66,811
4σ	99.99366	63.4	99.3790	6,210
5σ	99.99943	0.57	99.97674	233
6σ	99.999998	0.002	99.99966	3.4

Regardless of unforeseeable defects and various movements emerging in the long term, the 1.5 σ shift in the average is utilized as a kind of correction factor. In this way, a 1.5 σ shift in the average makes the process even more robust. The defect rates acquired below the 1.5 σ shift assumption are considered reliable even from the most pessimistic point of view. When the process average is shifted 1.5 σ , the normal distribution table value is reduced 1.5 σ in order to calculate the defect rates. For instance, in case of a 1.5 σ shift, the defect rate of 3.4 in a million corresponds to 4.5 σ instead of 6 σ in the normal distribution. Since 1.5 σ shift affects only one direction, it should be taken into consideration that only the defect rates on one side of the average, where a shift is present, shall be calculated. Since the value on the side, where no shift is present, will be negligibly small, it is ignored (Firuzan & Kuvvetli, 2012).

CHAPTER THREE

APPLICATION

3.1 Scope of Project

The world's largest industry is the automotive industry and subject to constant change. Organizations active within the automotive industry have to upgrade product quality and delivery continuously, decrease material and labor costs, and nonconformity rates. Low-quality components infiltrating the supply chain cause significant problems for the vehicle manufacturers (Hoyle, 2005). Any feature or characteristic of a service/product which is required to satisfied customer requests or achieves the capability for use is a quality characteristic (Hoyle, 2000). Any manufacturers are no longer single responsible for producing parts of one specific product wholly. Companies use standards to reducing the diversity of processes and approaches (Clarke, 2005).

In this chapter of the thesis, the Six Sigma project conducted at a company manufacturing rubber products for the automotive industry and the application of statistical techniques is discussed.

The reason of choice for the rubber manufacturing company is that the company applies not just widely accepted industrial standards but is also compliant with the specific quality standards and procedures of the customer quality systems (Ford Q1 certificate etc.).

The flexibility problem of the front door glass seal manufactured from rubber at the factory in Turkey for ABC make cars constitute the scope of this project.

3.2. Company Information about the Application

The rubber producing company is a manufacturer on the universal scale and active in four continents with seven factories. The company is manufacturing rubber and

plastic-derivative products for the automotive industry where the competition is fierce counts as one of the top actors in the sector. The aim of the company is to drive the quality of its products to the utmost level in line with the continuous improvement mentality. In this regard, constant “benchmarking” is conducted with competing companies. New and low-cost raw materials are developed by using the latest technology available. Various physical, chemical, performance and conditioning tests on the products and raw materials are carried out. Zero ppm value is targeted at production facilities.

As of July 2016, the company employs approximately 8500 personnel, 76% being active in the production and the remaining 24% being active administration, technical and management departments. In Figure 3.1, educational background of the company personnel is shown.

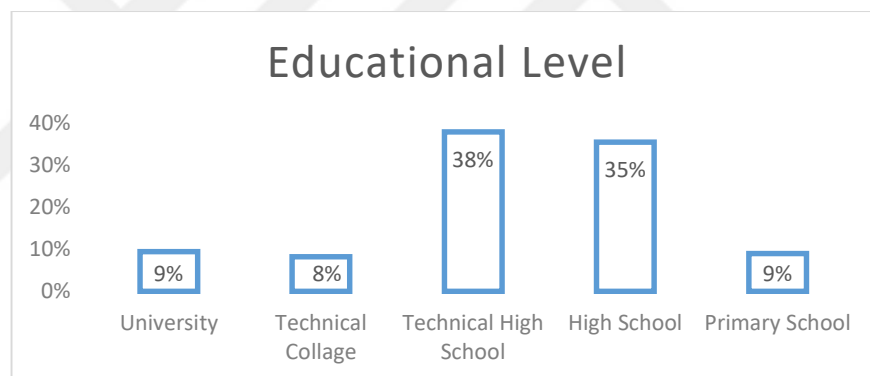


Figure 3.1 Educational level of rubber Producer Company's

The number of employees is steadily rising as a result of the continuous capacity enhancements of the company.

3.3 Purpose of Application

This thesis proposes to optimize the door seal manufacturing process in rubber Producer Company by reducing the defects caused in the process. This project focuses on improving the process, minimizing losses, and dropping faults by using the Six Sigma DMAIC methodology.

The rubber manufacturer as the main supplier of the globally leading ABC car brand receives lately customer complaints about the flexibility of the door glass seals produced.

It is aimed at this study to improve the factors causing the customer complaints by using the Six Sigma. As extensively known, Six Sigma is one of the most convenient ways to succeed the process due to the prioritizing of the customer and the incorporation of incidents and data for the best solution (Pande & Holpp, 2001).

Six Sigma team aims to develop the process rather than the product (Mast, 2006). To this end, the sources of variation shall be identified and eliminated (McCarty et al., 2004). By using the Six Sigma methodology, the factors triggering the customer complaints will be detected and improved.

3.4 Application Method

In today's complicated manufacturing atmosphere, it is essential that companies continually develop their business processes, to sustain their competitive market. The industrial statistical field has entered many statistical techniques for managing and improving processes in numerous industries (Joglekar 2010; Montgomery 2012; Montgomery & Runger 2013; Prashar, 2016).

In the modern competitive market, the chances of survival for the company making mistakes is rather low. Therefore, the Six Sigma team aims to minimize the possible defect sources by taking the production process under control. To achieve this goal various statistical and not statistical techniques and tool are employed.

Six Sigma methodology is selected for encompassing most of these techniques. Six Sigma strives to improve the performance and effectiveness of the process. Hence, the Six Sigma team preferred the Six Sigma DMAIC methodology as the application method. In various phases of DMAIC, many statistical techniques such as Taguchi experiment design etc. is used. By this way, products of higher quality will be

manufactured, costs are lowered, and efficiency and customer satisfaction will be enhanced.

3.5 Application Phases

Six Sigma is a methodological approach that is designed for continuous process improvement in operational excellence (Zhang et al., 2015). The Six Sigma is divided into five interconnected phase. These phases called respectively as define, measure, analyze, improve and control. “The DMAIC process is the centerpiece of the Six-Sigma problem-solving methodology, and is recommended for the systematic handling of any project. The tools of Six Sigma and operational excellence are most often applied within the framework of DMAIC” (Cabrita et al., 2016, p. 223). The comprehensive contents and series of application of DMAIC tools could differ from one company to another and from project to project (Goh, 2002).

The reason for the company to apply DMAIC methodology is that the method enables the application of various statistical and not statistical tools along with the problem being viewed within a methodology.

DMAIC projects can be developed using a top-down or bottom-up approach (Lynch et al., 2003). The Six Sigma team applied the DMAIC methodology along with the requirements and capabilities of the rubber manufacturing company.

3.5.1 Define Phase

The first phase of the Six Sigma study is the definition phase of the DMAIC problem-solving method. According to Henderson & Evans (2000), problems and customer requirements are defined in this phase. In this step, the indications, goals, and limitations of the project are defined in a way apprehensible by every individual and the effect on the customer is determined. Since the definition phase constitutes the initial stage of the project start, establishing the correct metrics are of importance to be able to reach suitable solutions in the following phases.

As the first step of this Six Sigma project, the customer complaint of the ABC car manufacturer concerning the front door glass jamming and the glass coming loose off the seal housing is defined.

It was detected that most of the customer complaints were about the glass jamming at times and therefore not being able to complete the upwards/downwards movement during the opening and closing of the electrically actuated front door glass or the glass coming loose off the seal housing. The glass actuator automatically locks itself out and becomes inactive to minimize the problems caused by jamming. ABC car manufacturer detected that the problem is caused by the front door glass seals. Therefore, the scope of the Six Sigma project is the door glass seal with the part number MTA2034, manufactured for ABC Car Company.

The Six Sigma project is only limited to the MTA2034 front door glass seal used for ABC cars. Front door glass seals manufactured for other models of this firm are excluded from the scope of this project.

Six Sigma designated a period of 12 months for the implementation of the project. According to the Six Sigma DMAIC methodology, schedule for each planned step is shown in Figure 3.2.

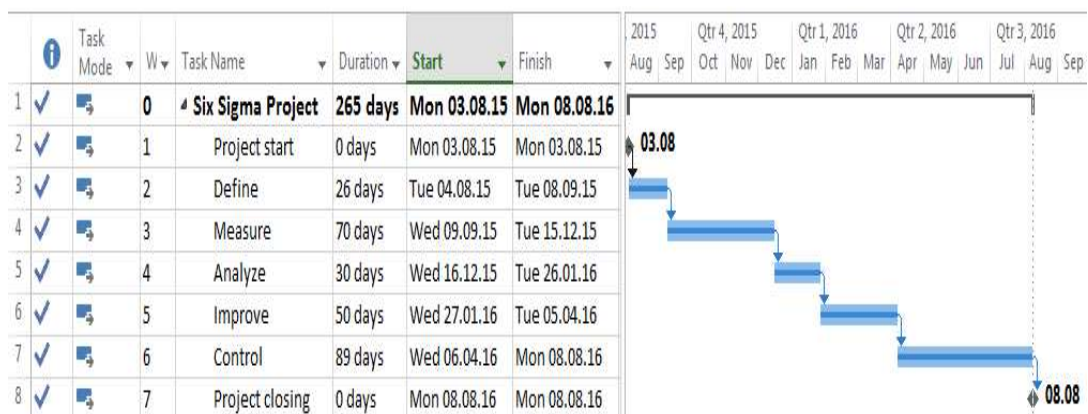


Figure 3.2 Project schedule

In reviews conducted by ABC car manufacturer, an increase of customer complaints was detected concerning the glass door seals procured from the rubber

manufacturing company. ABC car manufacturer notified the rubber manufacturing company of the aforementioned customer complaint.

The rubber manufacturing company forms a Six Sigma team to solve the problem triggering the customer complaints of ABC car manufacturer and to prevent recurrence. Team members are as follows:

- Product group administrator.
- Continuous improvement manager.
- Project quality engineer.
- Quality manager.
- R&D engineer.
- The foreman of the line manufacturing for the ABC car company and an experienced blue-collar worker involved in the operation.
- Finance department personnel.

Six Sigma team is formed among competent employees, working at relevant departments or cooperating actively in addition to that on a voluntary basis. “Continuous improvement manager” with a black belt is selected as the team leader.

Employees of the company provide the required labor for the project. The required financial resources are allocated 50% from R&D department budget, 30% production department budget and 20% customer relations department budget.

3.5.2 Measure Phase

Measurement system analysis (Gage R&R) is verified in this step (Prashar, 2016). The aim of the Gage R&R studies is applied to ensure that the measurement system is statistically reliable. Measurement system analyzes (Gage R&R study) evaluate how much of the total variance is due to the measurement system related. (Kaushik & Khanduja, 2009). As point out Kumar et al. (2006, p. 413), “a gauge repeatability and reproducibility (R&R) study was conducted to identify the sources of variation in the measurement system and to determine whether it was accurate or not”.

Six Sigma team aims to collect data on the flexibility of the seals and evaluate the results. At first, the Six Sigma team examines the door glass seal in detail. Glass seals ensure that the moving glasses of the car operate silently and with the minimum friction possible in the housing. Also, these seals help to isolate dust, heat, water, and noise, thus contributing to the cleanliness of the windows.

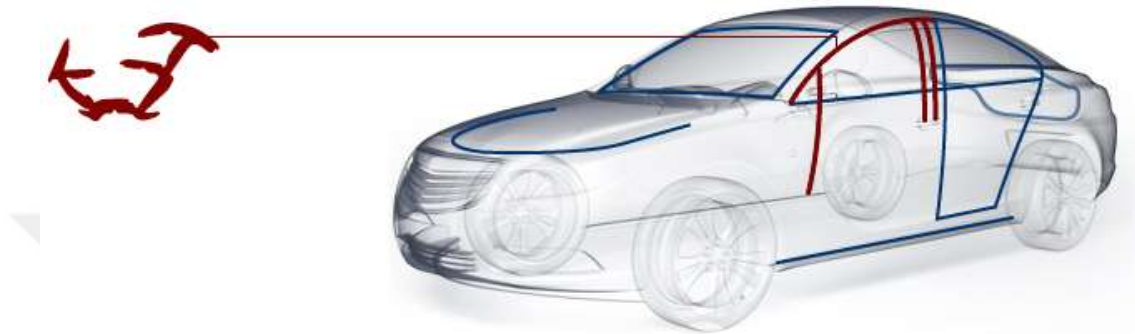


Figure 3.3 Location of the front door glass seal on a vehicle

The location of the glass seal on the vehicle is shown in Figure 3.3. Glasses move inside the housing indicated with red color lines. The glass should move with a certain degree of flexibility in the seal. Therefore, Six Sigma team examined the technical characteristics of the door glass seal and product standards thereof.

The flexibility of the front door glass seal was determined as the quality characteristic that caused the customer complaint. ABC provides the technical specification to the rubber producer company states the limits as 9 ± 2 Newton. The rubber manufacturing company inspects the product “online” for mastic and outer surface damage following production and the measurements for the flexibility of the glass seal are conducted according to the equivalent of globally accepted quality standards with the device shown in Figure 3.4. The measurement device is compliant with ISO 178 and ASTM D970 quality standards.

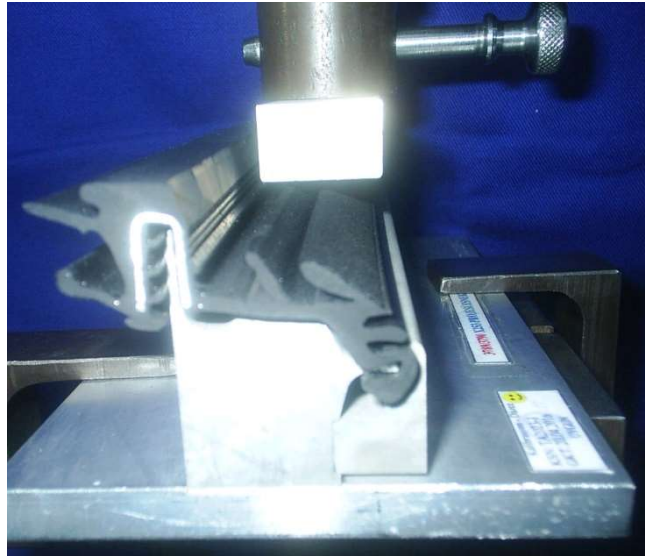


Figure 3.4 Flexibility test (Personal archive, 2015)

Glass seal with the part number MTA2034 produced for ABC Car Company is manufactured only on the machine with the code number X15. Production department works six workdays and three shifts. In every shift, one operator mans the machine, code no. X15. Only MTA2034 glass seals for the ABC Company are manufactured with this machine.

An average of 350 glass profiles per shift is produced at the rubber manufacturer. Producer company of rubber produces yearly 327,600 (350 qt./shift * 3 shifts * 26 work days * 12 months) MTA2034 door glass seals in average.

A total variation consists of the measurement system variation and process variation. To determine the actual process variation in the Six Sigma projects, principally the measurement system needs to be confirmed (Aized, 2012; Breyfogle, 1999; Eckes, 2001; Hahn, Doganaksoy & Hoerl, 2000; Pande et al., 2000; Rasis, Gitlow & Popovich, 2002).

$$\sigma_{Total}^2 = \sigma_{Process}^2 + \sigma_{Measurement\ system}^2 \quad (3.1)$$

Measurements are critical components of any quality system. Measurement is an inseparable constituent of DMAIC problem-solving process. An ineffective measurement system can affect the work performance adversely, due to the possibility

of an incorrect decision-making. Goals of the measurement system competence research are as follows (Montgomery, 2009):

- Understand how much of the total variance observed are due to the measurement system.
- Separate variance elements in the measurement system.
- Evaluate the competence of the measurement system.

Therefore, the Six Sigma team chose to identify the variance resulting from the measurement system and separate it from the process variance to determine the actual process variance.

Measurement system variance consists of two components; reproducibility and repeatability. Repeatability is the variance of a part between the measurements performed by an operator with the same measurement device and under the same working conditions. Reproducibility is the variance of the average of measurements performed by different operators on the same part with the same measurement device (Joglekar, 2003).

$$\sigma_{Measurement\ system}^2 = \sigma_{Repeatability}^2 + \sigma_{Reproducibility}^2 \quad (3.2)$$

In order to determine the measurement system variance, the Six Sigma team performs measurements in accordance with the request of ABC car manufacturer. Measurements are conducted on unformed five single parts with three repetitions, manufactured at different times in three shifts. Each one of these five parts are cut into nine equal pieces with a length of 40 cm. To achieve the randomly in the part selection, operators do not know which box contains the parts of which profile and the order of parts. Measurements are performed destructively. Measurement results of front door seals are given in Table 3.1.

Table 3.1 Gage R&R measurement result

Operator	Part 1	Part 2	Part 3	Part 4	Part 5
A	6.91	7.15	6.99	6.88	6.90
A	6.92	7.19	7.00	6.89	6.91
A	6.92	7.19	7.00	6.89	6.91
B	7.14	7.36	7.18	7.25	7.09
B	7.01	7.31	7.11	7.21	7.01
B	7.09	7.31	7.11	7.21	7.01
C	6.97	7.32	6.83	7.29	6.98
C	6.98	7.39	6.89	7.29	6.99
C	6.98	7.39	6.89	7.29	6.99

Primarily, a normality test was conducted to be able to perform a measurement system analysis on the collected data. The results of the trial are shown in Figure 3.5.

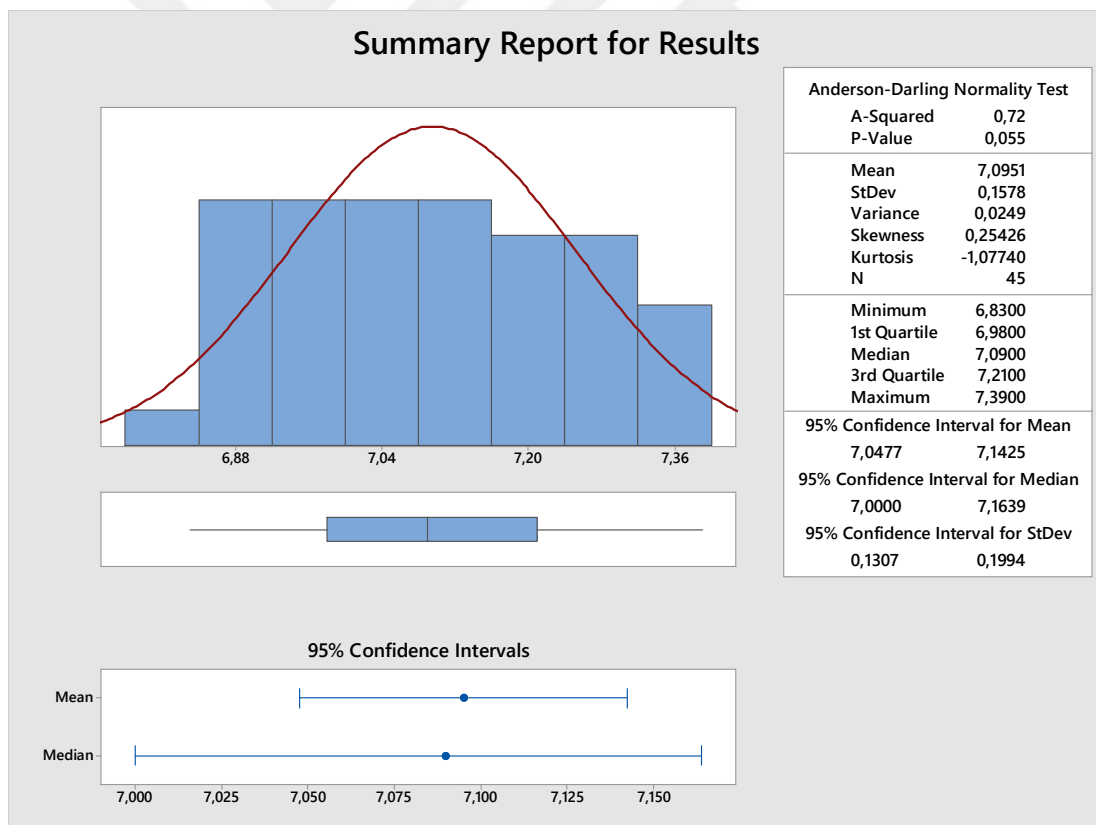


Figure 3.5 Gage R & R data normality test

According to the Anderson-Darling Normality Test; A-Squared value was determined as 0.72 and P-Value as 0.055. These values show that the data is distributed normally.

Measurement system analysis is performed in consequence of the normal distribution of the data. The measurement system analysis is shown in Figure 3.6.

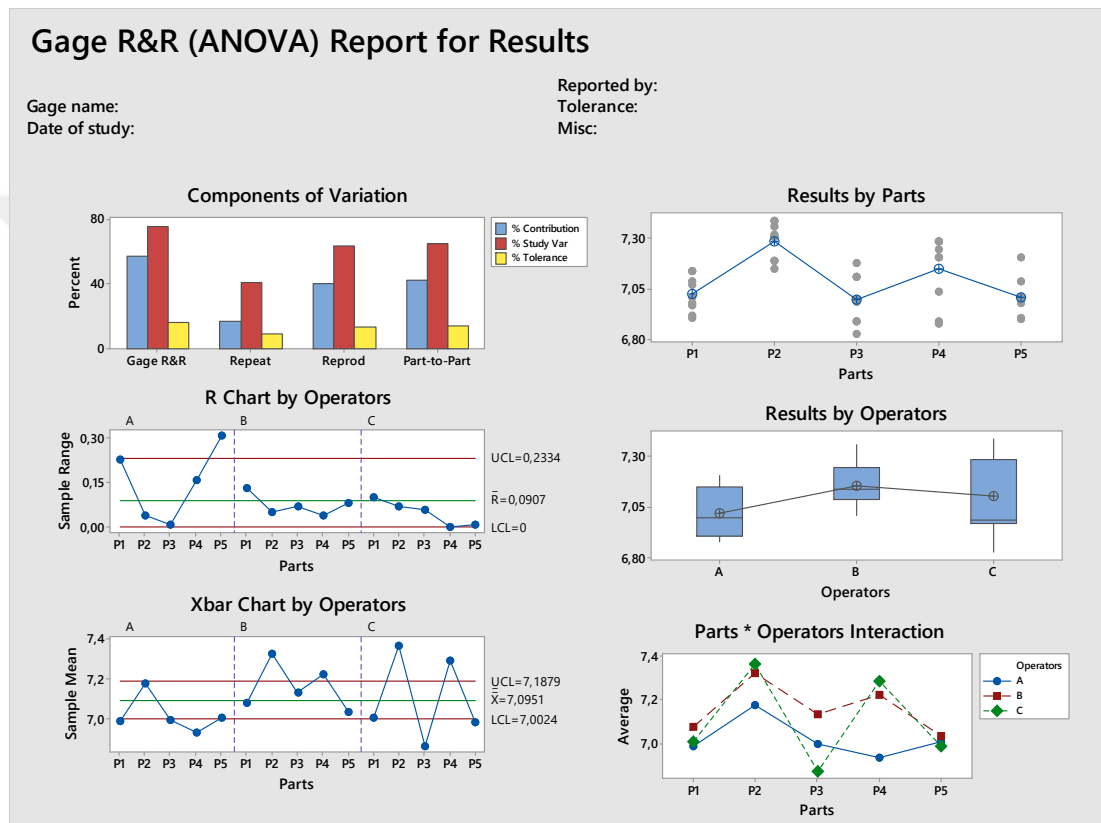


Figure 3.6 Gage R & R analysis result

The evaluation of Gage R&R results is given in Figure 3.6 and Table 3.3 ANOVA report.

%Study Variance bars show that the 75.77% of the variance results from the measurement system. For a good measurement system, it is expected that the variance caused by the measurement system is smaller in comparison with the part-to-part variance. If Gage R&R, reproducibility and repeatability bars column are high, that means the measurement system is unstable (George et al., 2005). In Figure 3.6, the

variance caused by the measurement system being bigger shows that the measurement system is inadequate.

Results by parts show the measurement values and averages taken for each part. In this chart, it is desirable that the data collected for each part overlap each other. However, it can be seen in Figure 3.6 that the measurement variance of the parts is excessive.

In the R Chart by Operators, it is expected that the range of the values measured by the operator for each part is smaller. Measurement ranges being under control show the consistency between the measurements of the operators. In Figure 3.6, it can be seen that especially the measurements of operator “A” is bigger than the variance of the measurement results of operators’ B and C.

In chart Results by Operators, horizontal line tilting shows the effect of the operators. If the line connecting the means is flat or almost flat, there are no significant differences between operators (George et al., 2005). In Figure 3.6, it is seen that the variance between the operators is big. The line is expected to be straight so that the variance among by the operators is at a minimum.

\bar{x} Chart by Operators shows whether the variance is a result of the measurement system or the process itself. In this chart, it is an expected condition that the cause of the variance is not the measurement system but rather the process itself. Measurements being within control limits shows that an incorrect or faulty measurement system was employed. In this case, the variance caused by the parts are bigger than the variance caused by the measurement system. In Figure 3.6, the result of the \bar{X} chart shows that the measurement system is inadequate.

Parts*Operators Interaction shows the interaction of operators and parts. In case there is no interaction, parallel or overlapping laps are seen. Therefore, it is a favored condition that the lines are parallel to or overlapping each other. When Figure 3.6 is examined again, it can be seen that a strong interaction exists.

Table 3.2 Gage R&R Study - Anova

Gage R&R Study - ANOVA Method					
Two-Way ANOVA Table with Interaction					
Source	DF	SS	MS	F	P
Parts	4	0.55910	0.139776	4.52169	0.033
Operators	2	0.14599	0.072996	2.36138	0.156
Parts * Operators	8	0.24730	0.030912	6.45199	0.000
Repeatability	30	0.14373	0.004791		
Total	44	1.09612			

α to remove interaction term = 0.05

Gage R&R		
Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0163037	57.41
Repeatability	0.0047911	16.87
Reproducibility	0.0115126	40.54
Operators	0.0028056	9.88
Operators*Parts	0.0087070	30.66
Part-To-Part	0.0120959	42.59
Total Variation	0.0283996	100.00

Process tolerance = 4

Source	StdDev (SD)	Study Var (5.15 × SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	0.127686	0.657583	75.77	16.44
Repeatability	0.069218	0.356472	41.07	8.91
Reproducibility	0.107297	0.552578	63.67	13.81
Operators	0.052967	0.272783	31.43	6.82
Operators*Parts	0.093312	0.480554	55.37	12.01
Part-To-Part	0.109981	0.566405	65.26	14.16
Total Variation	0.168522	0.867888	100.00	21.70

Number of Distinct Categories = 1

Study Variance has been determined as R&R %= 75.77 %. R&R % being > 30% shows that an inadequate measurement system is employed to see the actual process variance (Automotive Industry Action Group [AIAG], 2010; Airbus, 2011).

Number of Distinct Categories: If a number of distinct categories is equal five or greater than this value, the measurement system can discern over five groups within the data range and is often considered to have acceptable discrimination (AIAG, 2010; Airbus, 2011). However, this value is equal to 1 in Table 3.2 shows that the measurement system is utterly inadequate.

A high reproducibility value with 63.67 % has been determined. Possible reasons for this condition is the difference between operators. Six Sigma team decides to research the causes of this difference. Reproducibility value being under 10 % shows that the measurement system is highly sufficient.

A high repeatability value with 41.07 % has been detected. As maintenance, repair, calibration, etc. requirements of the measurement devices might be the reason for this condition, Six Sigma team requested an examination from the maintenance department of the factory. It is accepted in AIAG (2010) that the repeatability value being between 10-30 % is marginal. The calibration of the measurement device has been verified, and it was detected that the calibration values are conforming.

By all these analysis results showing the inadequacy of the measurement system, the reasons are examined in detail. Brainstorming and Ishikawa's cause-and-effect diagram was used to this end.

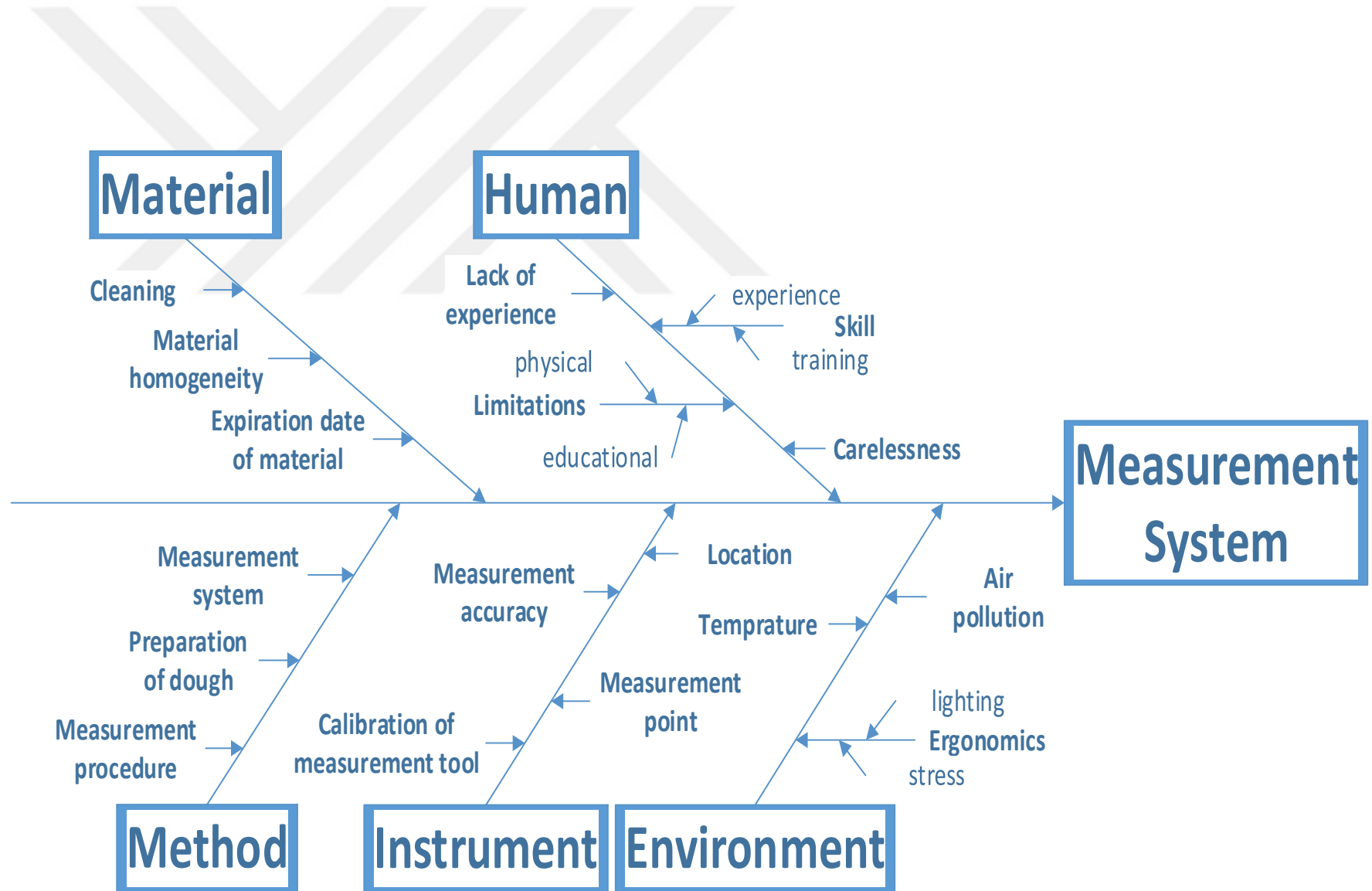


Figure 3.7 Cause and effect analysis of the measurement system errors

Six Sigma team researched the factors causing the inadequacy of the measurement system by focusing on the factors defined in the cause-and-effect diagram.

It shall be ensured that before front door glass seal is inserted into the measurement device no foreign object such as burrs etc. is present. Such debris may prevent the glass seal from seating properly in the measurement device and cause incorrect measurement results. In the review conducted by the Six Sigma team, it was detected that the cleanliness of the measurement device and environmental conditions were neglected. On this matter, training sessions for the personnel working in all three shifts and the responsible managers were held. It was requested to make sure that the areas in contact with the rubber shall be clean before inserting the glass seal into the measurement device. To this end, “rubber burr, etc. waste inspection on the seal and/or measurement device” clause was included in the inspection plan.

Door glass seal no. MTA2034 consists of four different main doughs. Doughs are formed in computer-controlled, automatic mixing machines. Inspections showed that the dough is highly homogenous.

Goods in/out tracking process of the dough are conducted digitally, and the dough is consumed before the one-month expiry date. Doughs prepared in mixers with 145 liters’ capacity are stored in cold storage facilities to prevent them being affected by the environmental and weather conditions. Doughs remain in the storage ten days in average, due to the application of First-in, First-out principle. Specifications state the storage period of dough in cold storage facilities as one month.

Flexibility measurement value is shown on the screen of the machine with a big font size. Therefore, no hindrance regarding the physical conditions was determined.

Since all three personnel working in the section have a technical high school background, they do possess the capability to work in the process. No nonconformities regarding the educational background of the personnel were detected.

Experience is a determining factor in the measurement device usage. Rubber manufacturer considers the working hours of the personnel a sufficient period to gain experience. Hence, no irregularities regarding the lack of experience were detected at the first stage.

Technical training records of the personnel were examined. Measurements are conducted through destructive tests. Therefore, seals produced as a single piece are separated by 40 cm long, equal pieces for the measurement process. Each personnel were observed during the measurement process. As a result of this observation, it was detected that the seal pieces to be measured are inserted into the device differently. Measurement shall be conducted after the seal is seated flat into the grooves of the measurement device. However, measuring the seal without being correctly seated delivers varying measurement results. Six Sigma team arranged training for the personnel regarding the correct usage of the measurement system and recording the results. Six Sigma team also requested regular, yearly recurring training on the issue.

The stress level of the personnel affects the accuracy of the measurements and the quality of the work. Keeping the stress level under control helps the operators to show required sensitivity. The personnel assigned to this process were briefed on this matter with a training session. Department managers were also asked to pay the utmost attention to this issue.

Measurements are conducted by placing glass door seals into the measurement device as requested by the customer. As a preventive action, recurrence training was conducted on how to correctly insert the glass seal into the measurement device and conducting the measurement.

Doughs are prepared in automated machines, fully controlled by computers. Each stage of the dough production is directed by the computer system.

A training session was arranged for the measurement procedure, and three operators working in the process were informed on the procedure.

Measurement sensitivity of the machine is complying with the customer specifications and international standards, therefore suitable for this particular process.

The measurement device is visually inspected each day by the operator, maintained, and controlled with monthly periods by the maintenance department. As shown in Table 3.3, a high repeatability value such as 41.07% shows that a nonconformity may be present, caused by the measurement device. Therefore, maintenance team repeated the maintenance and fixture settings of the measurement device.

The measurement device is calibrated with six-month periods. Following the customer complaint, the calibration of the measurement device is verified.

It was detected that the temperature of the working environment was 22 ± 2 °C and the lighting was at 3000 lux. Environmental temperature is fairly suitable for the production. However, the lighting was improved, and the emittance was raised up to 4000 lux.

In order to bring the measurement system to the adequate level, the company implemented required improvements regarding the factors given in Figure 3.7. Following the corrective and preventive actions, glass seal flexibility measurements were completed. Measurement results are shown in Table 3.3.

Table 3.3 New Gage R&R results

Operator	Part 1	Part 2	Part 3	Part 4	Part 5
A	8.52	8.57	8.55	8.58	8.62
A	8.52	8.58	8.55	8.56	8.62
A	8.53	8.58	8.55	8.57	8.62
B	8.52	8.57	8.56	8.58	8.62
B	8.52	8.57	8.55	8.58	8.62
B	8.53	8.58	8.57	8.57	8.61
C	8.53	8.56	8.57	8.59	8.61
C	8.51	8.57	8.56	8.59	8.61
C	8.51	8.57	8.55	8.59	8.61

New measurement data have been tested for normality. As shown in Figure 3.8, the data are normally distributed.

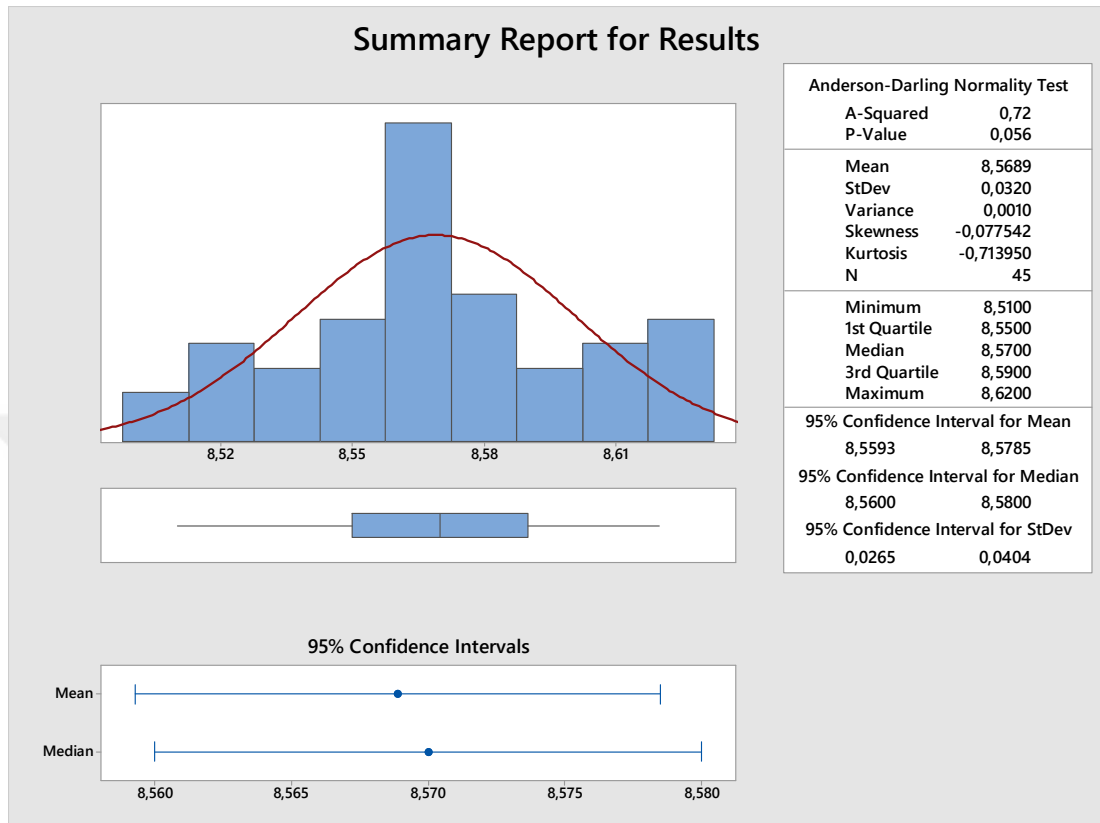


Figure 3.8 Normality test for new measurement result

In consequence of the normal distribution of the data, measurement system analysis was performed. Analysis results are given in Figure 3.9 as a diagram and in Table 3.4 in analysis format.

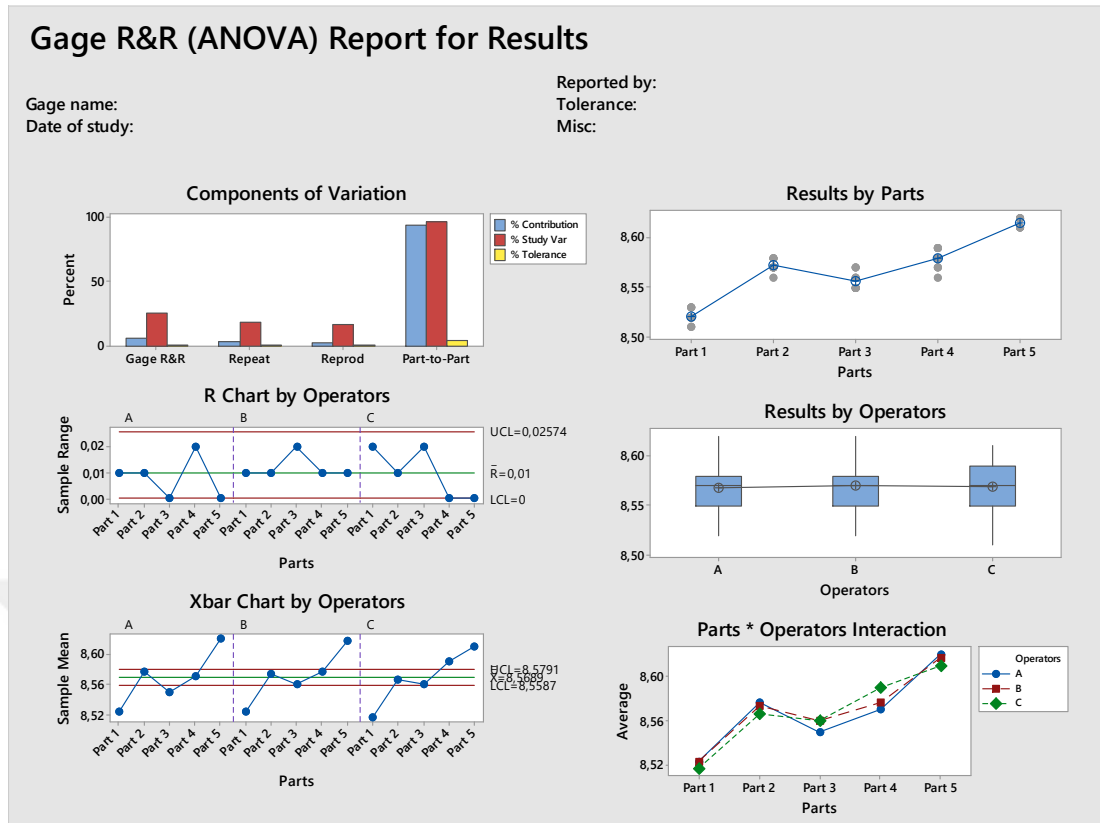


Figure 3.9 Gage R&R analysis results of the new measurement results

Following the implementation of improvements, the variation value caused by the measurement system (components of variation) was taken down from 75.77% to 25.25%.

Results by Parts shows the measurements were taken for each part and the average values. As shown in Figure 3.9 the measurement variance of the parts was reduced. It can be seen that especially the measurement results of the 5th part is quite close.

R Chart by Operators shows the consistency between the measurements of the operators, measurement results being under control. It can be seen that the measurements of all five parts conducted by each operator are within the control limits of the range.

Results by Operators shows the effect of the operators on the measurements. The measurements of operator B vary only insignificantly from those of the operator A and

C. It is expected that the horizontal line is straight to prove the measurement difference between the operators are at a minimum level. Here too, there is a very small difference in the B operator.

\bar{x} Chart by Operators shows that the measurement system is adequate. Measurements being outside the control limits shows that the variation is caused by the variability of parts.

Parts * Operators Interaction graph shows that the lines are parallel to one another and that there is no interaction between the two. This situation, measurement is a desirable condition in the analysis of the site.

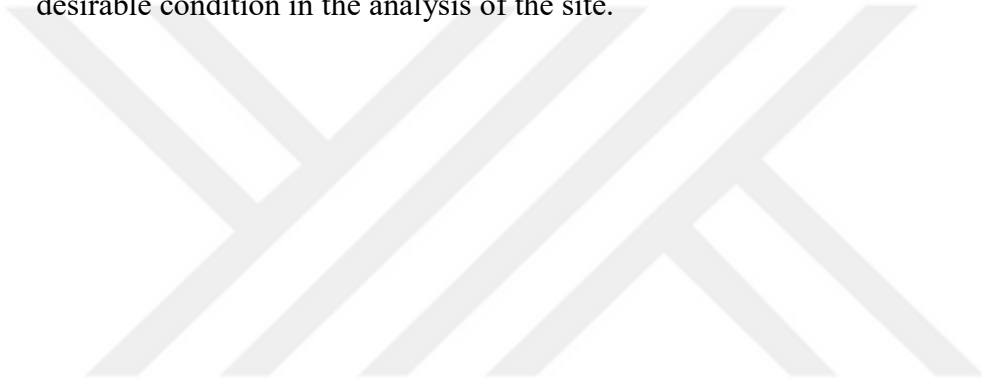


Table 3.4 Gage R&R Study – ANOVA for new data

Gage R&R Study - ANOVA Method					
Two-Way ANOVA Table with Interaction					
Source	DF	SS	MS	F	P
Parts	4	0.0424889	0.0106222	71.3433	0.000
Operators	2	0.0000311	0.0000156	0.1045	0.902
Parts * Operators	8	0.0011911	0.0001489	3.3500	0.007
Repeatability	30	0.0013333	0.0000444		
Total	44	0.0450444			

α to remove interaction term = 0.05

Gage R&R		
Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0000793	6.38
Repeatability	0.0000444	3.58
Reproducibility	0.0000348	2.80
Operators	0.0000000	0.00
Operators*Parts	0.0000348	2.80
Part-To-Part	0.0011637	93.62
Total Variation	0.0012430	100.00

Process tolerance = 4

Source	StdDev (SD)	Study Var (5.15 × SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	0.0089028	0.045849	25.25	1.15
Repeatability	0.0066667	0.034333	18.91	0.86
Reproducibility	0.0059004	0.030387	16.74	0.76
Operators	0.0000000	0.000000	0.00	0.00
Operators*Parts	0.0059004	0.030387	16.74	0.76
Part-To-Part	0.0341131	0.175682	96.76	4.39
Total Variation	0.0352557	0.181567	100.00	4.54

Number of Distinct Categories = 5

In accordance with the new measurement results, ANOVA results of the acquired data are evaluated.

Study variance was reduced to Study Variance (R&R%) = 25.25%. R&R% being <30% shows that the measurement system was marginally suitable. This value is accepted by the customer. Another comparing value, % contribution value is calculated as 6.38. Since this value is 2% < % Contribution < 9%, it is another evidence for the conditional acceptability with customer approval.

Number of Distinct Categories: In Table 3.4, the discriminant value was five. If the number of distinct categories is greater than five, the measurement system can discern over five groups within the data range and is often considered to have acceptable discrimination (McCarty et al., 2004).

As a result of the improvements performed on the measurement system the variance caused by the measurement system was reduced from 75.77% to 25.25%. This improvement rate achieved was defined as marginally acceptable by AIAG (2010). Following this phase, factors causing the self-variance of the process shall be analyzed.

3.5.3 Analyze Phase

According to Pyzdek (2003), current status of the process and the significant inputs and their levels causing the process variance are analyzed in this phase.

Six Sigma team collected data from the shop floor as requested by ABC car manufacturer in order to receive early warnings for the process variance and to check whether the process is under control. Since the measurements are performed through destructive tests, the data are collected from five measurements each shift for a 10-day long period. 150 measurements in total were performed and brought together under 30 sub-groups.

S1, S2, S3 indicate day, evening and night shifts respectively. Measurement results are given in Table 3.5.

Table 3.5 Result of measurements per shift

Shift	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10
S1	7.16	6.88	7.18	7.24	7.18	6.96	7.24	7.22	6.98	7.13
S1	7.08	7.10	7.29	7.05	6.95	6.99	7.15	7.06	6.98	7.17
S1	7.00	7.03	7.05	7.05	7.02	6.95	7.04	7.28	7.07	7.07
S1	7.09	7.26	7.11	6.96	6.99	7.12	6.99	7.17	7.12	7.27
S1	7.38	7.00	6.83	7.10	7.26	7.17	7.11	7.23	7.23	7.07
Average of S1	7.14	7.05	7.09	7.08	7.08	7.04	7.11	7.19	7.07	7.14
Range of S1	0.38	0.38	0.46	0.28	0.31	0.22	0.26	0.22	0.25	0.20
S2	7.20	7.28	7.07	7.17	7.06	7.20	7.02	6.94	7.35	6.95
S2	7.43	7.08	6.98	7.22	7.04	7.09	6.97	6.91	7.12	7.11
S2	7.23	7.39	7.04	7.15	7.10	6.79	7.42	7.19	7.32	7.03
S2	7.04	7.32	7.10	6.92	7.26	6.89	7.04	6.91	7.21	7.26
S2	7.08	7.07	7.18	7.04	7.25	7.09	7.06	6.93	7.05	6.89
Average of S2	7.20	7.23	7.07	7.10	7.14	7.01	7.10	6.98	7.21	7.05
Range of S2	0.39	0.32	0.20	0.30	0.22	0.41	0.45	0.29	0.29	0.37
S3	7.29	6.86	7.04	6.75	7.18	6.95	7.22	7.26	7.04	6.99
S3	6.78	7.02	6.95	6.98	7.16	6.93	7.16	6.82	6.97	6.97
S3	7.31	6.98	7.25	7.02	7.34	7.18	7.19	7.16	6.98	7.29
S3	6.88	7.21	7.07	7.11	6.94	7.20	7.02	7.04	7.20	6.96
S3	6.92	7.16	7.08	7.22	7.30	7.18	7.15	7.02	7.09	7.41
Average of S3	7.04	7.05	7.08	7.02	7.19	7.09	7.15	7.06	7.06	7.13
Range of S3	0.53	0.35	0.30	0.47	0.40	0.28	0.19	0.44	0.23	0.45

A normality test on the collected data was performed, the result of the test is given in Figure 3.10.

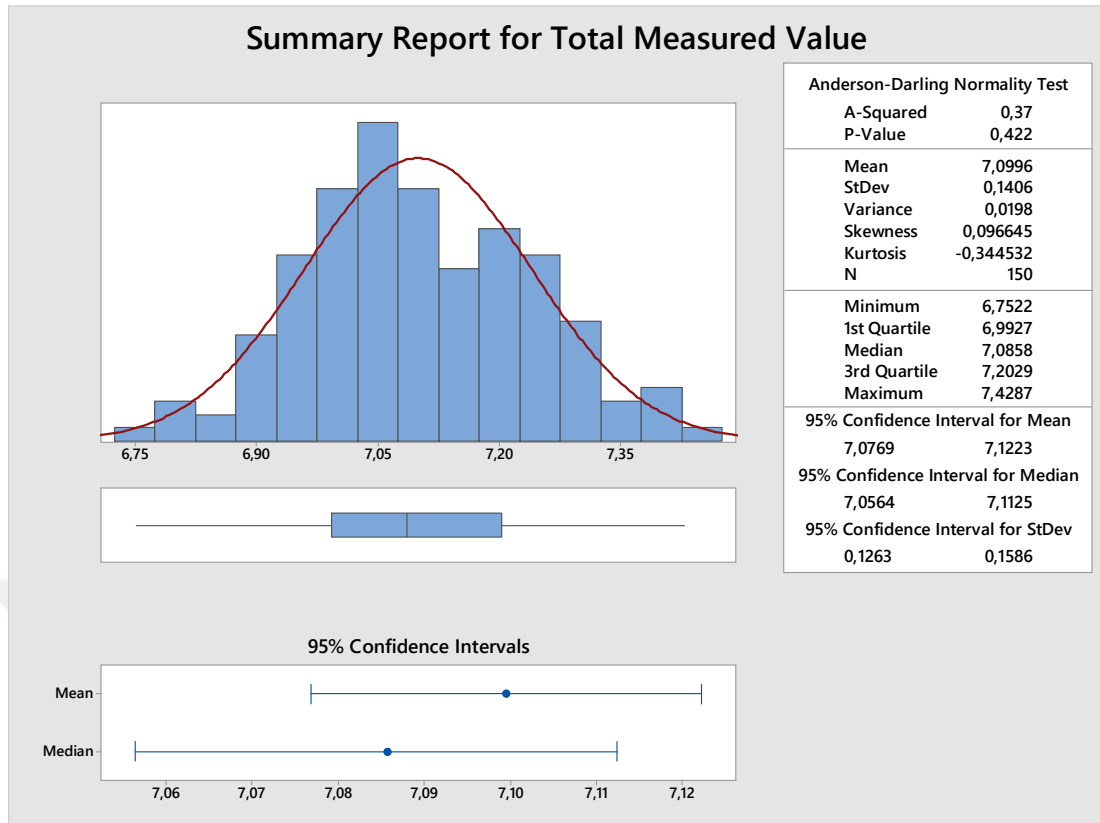


Figure 3.10 Results of normality test

In Figure 3.10, it is seen that the data is distributed normally. In order to see the stability of the process and whether the production is under control $\bar{X} - R$ control chart was arranged.

“Control charts are used to track a performance measure or key process indicator variable over time.... When a process measure is in control, its behavior on a control chart exhibits random variation when its distribution is stable” (Hsieh et al., 2007, p. 6).

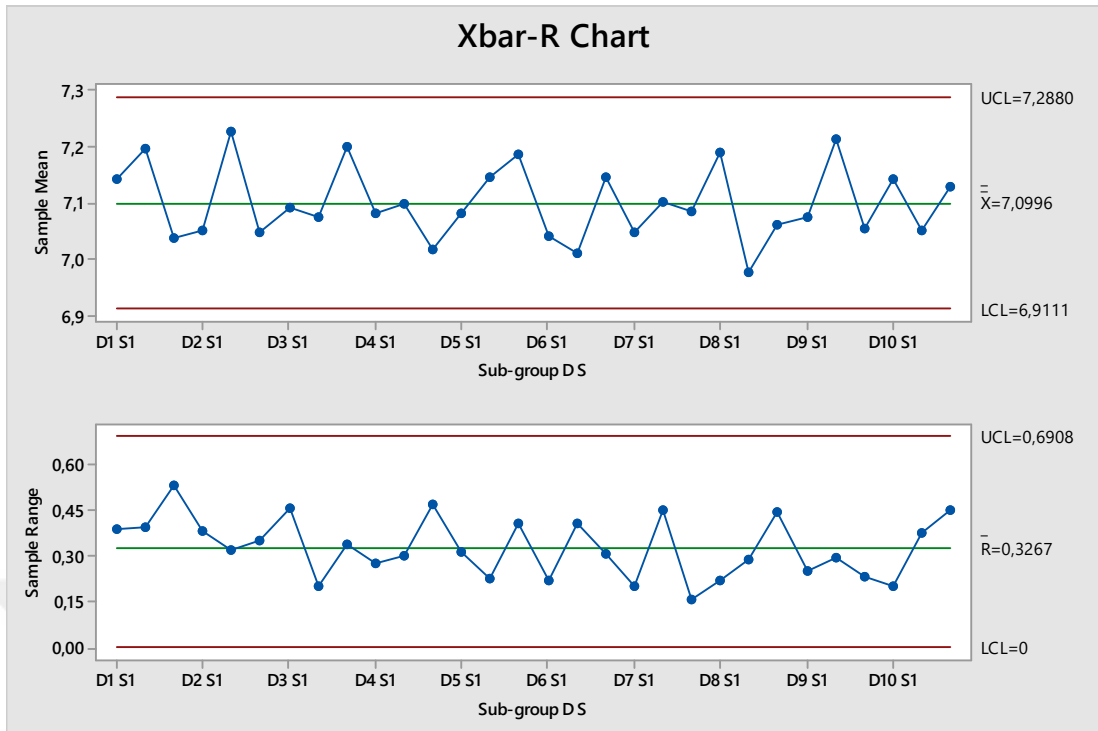


Figure 3.11 $\bar{x} - R$ control chart

In Figure 3.11 it can be seen that the production is under control. Six Sigma group investigated how much the process changes from the customer specification bounds by applying the process capability analysis as a statistical criterion (Montgomery, 2001).

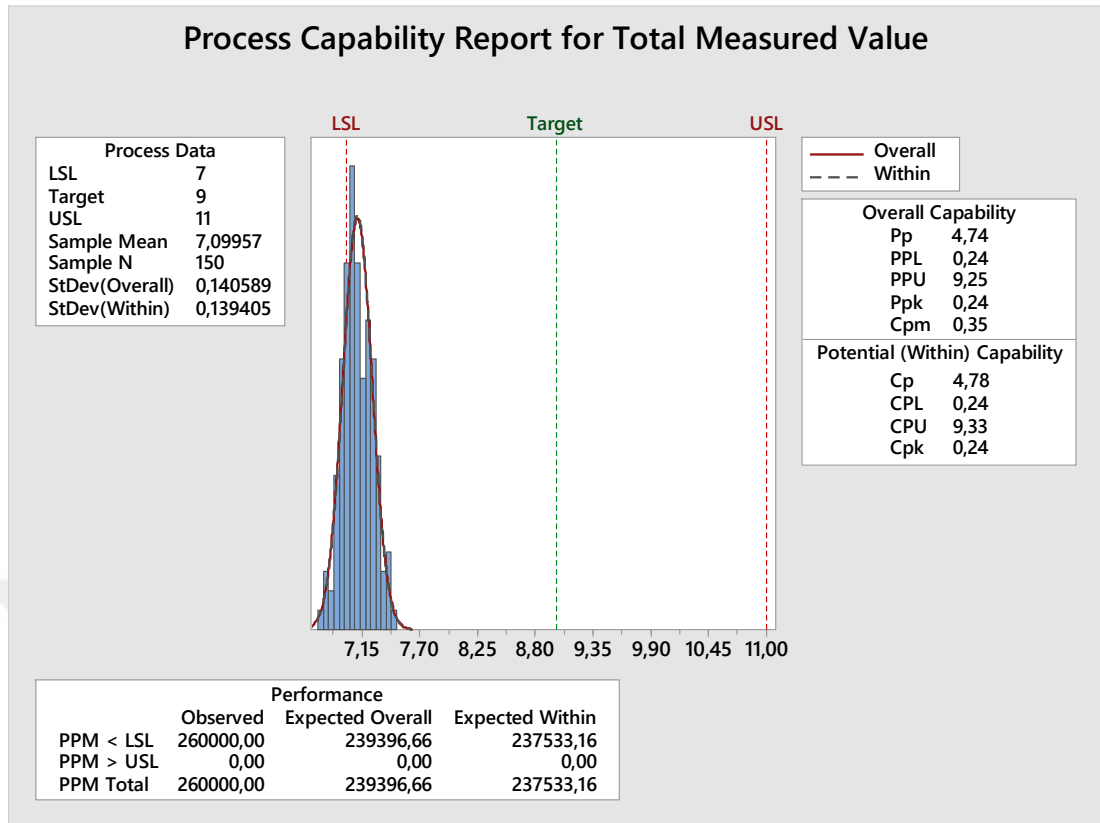


Figure 3.12 Process capability analysis

Process capability analysis results are given in Figure 3.12. Six Sigma team examined the C_{pk} value since the nominal (target) value did not coincide with the process mean (\bar{x}).

C_{pk} was calculated as 0.24. C_{pk} being < 1.33 shows that the process does not comply with the specification limits. Due to the normal distribution of the data “Expected Overall” performance value given in Figure 3.12 was examined in order to see the value of the nonconforming products in PPM. PPM_{Total} value was calculated as 239,396. 239,396 of every million MTA2034 parts produced with X15 machine do not comply with the flexibility limits stated in the contract requirements.

Appendix Table A1 shows that the quality level corresponding to the 239,396 nonconformities is 2.21σ . This shows that the company is capable of producing at the quality level 2.21σ .

It is seen that the process is stable, but the process capability is not at the wanted level ($C_{pk} > 1.33$) due to the sliding of the process mean to the lower specification limit. Therefore, the Six Sigma team calculated the process capability rate in order to see how much of the production line is being used. PCR calculation is as follows:

$$PCR = \frac{1}{C_p} = \frac{1}{4.78} = 0.209 \quad (3.3)$$

The company uses 20.9% of the production line, which is the desired value. Six Sigma team conducted an analysis of the current status to be able to pull up the process mean to the nominal value. Therefore;

- standard deviation ($\hat{\sigma}$),
- natural tolerance limits (*NTL*) and
- control limits (*CL*)

of the process are calculated respectively as follows:

$$\hat{\sigma} = \frac{\bar{R}}{d_2} = \frac{0.3267}{2.326} = 0.140589 \quad (3.4)$$

$$UCL_{\bar{X}} = \bar{\bar{x}} + A_2\bar{R} = 7.0996 + 0.577 \times 0.3267 = 7.2881059 \quad (3.5)$$

$$LCL_{\bar{X}} = \bar{\bar{x}} - A_2\bar{R} = 7.0996 - 0.577 \times 0.3267 = 6.9110941 \quad (3.6)$$

$$UNTL = \bar{\bar{x}} + 3\hat{\sigma} = 7.0996 + 3 \times 0.140589 = 7.521637 \quad (3.7)$$

$$LNNTL = \bar{\bar{x}} - 3\hat{\sigma} = 7.0996 - 3 \times 0.140589 = 6.677833 \quad (3.8)$$

$$p = P(X < LSL) = P\left(z < \frac{7-7.0996}{0.140589}\right) = P(z < -0.708) = 1 - 0.76115 = 0.2388 \quad (3.9)$$

Calculated results are collectively shown in Figure 3.13. It can be seen in the diagram that the lower control limit value (6.9110 Newton) is less than, the lower specification limit value (7 Newton).

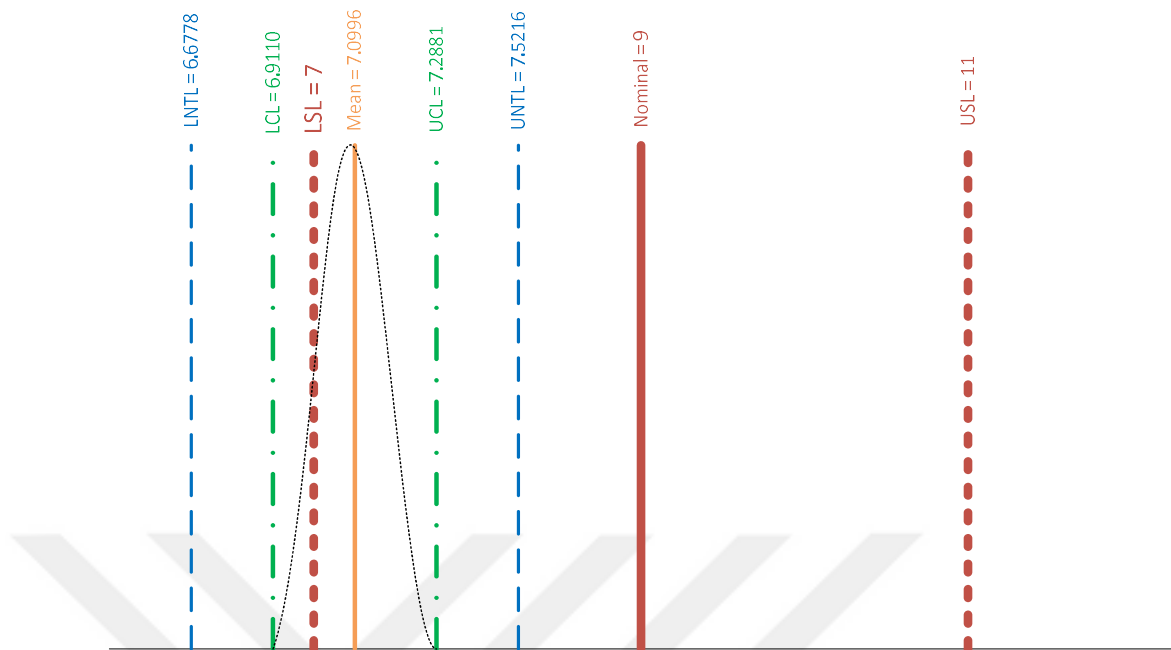


Figure 3.13 Comparison of tolerance limits

In this phase, it has been determined that the process is stable and the standard deviation ($\sigma=0.140589$) of the process is conforming. Process mean needs to be drawn closer to the nominal value. Six Sigma team intended to determine and eliminate the factor(s) causing the process varying from the nominal value.

To this end, Six Sigma team conducted research on the possible causes of the process variance by using the brainstorming technique and cause-and-effect analysis.

As a result of the research following cause-and-effect diagram was formed, shown in Figure 3.14.

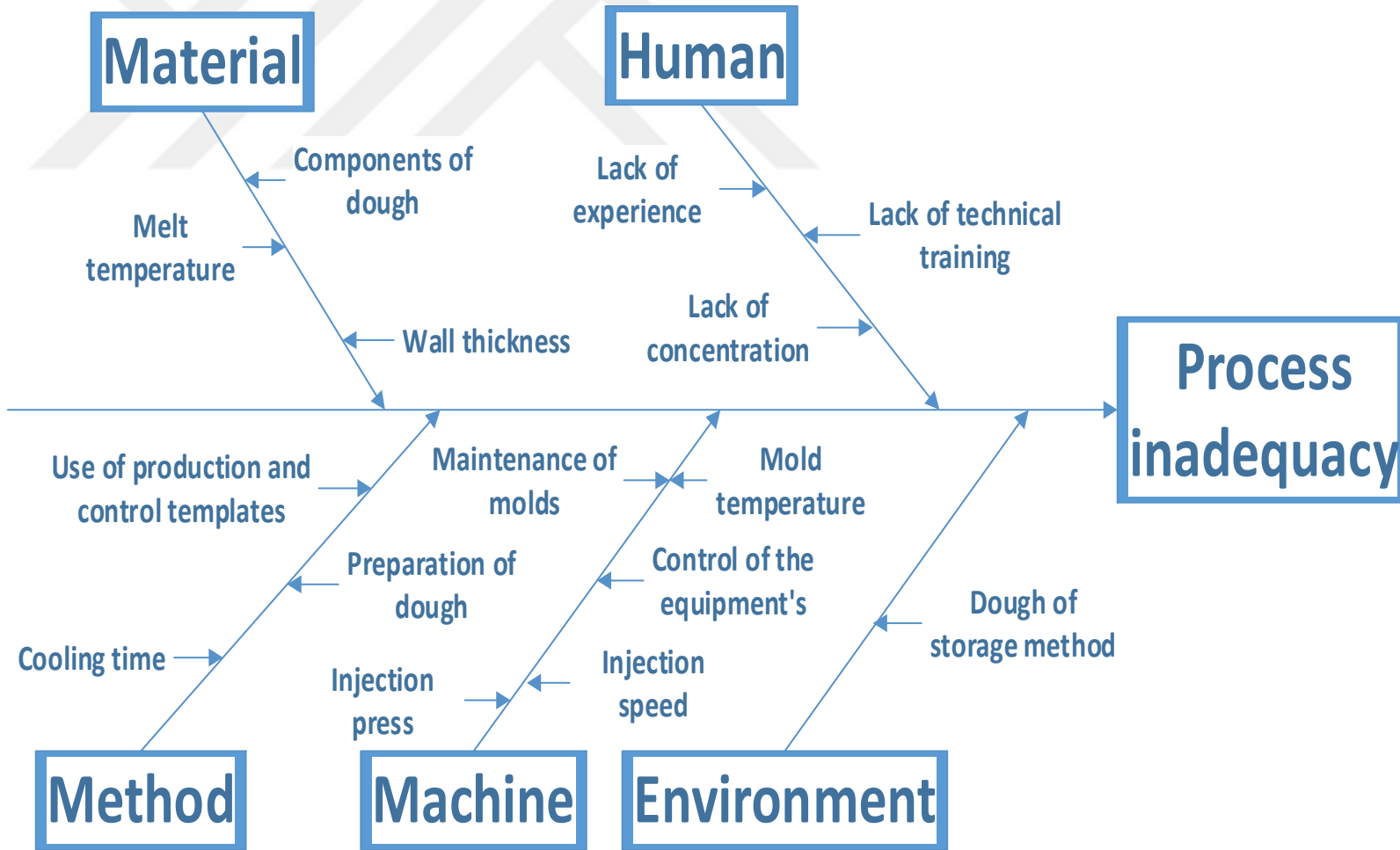


Figure 3.14 Ishikawa diagram for process incapability

Six Sigma team conducted a detailed study on the issues given in the cause-and-effect diagram in order to determine the root cause(s) of the variance. In this study, the factors that might have caused the process incapability are grouped together under the material, personnel, and method, machine and environment aspects.

The dough of the door glass seal no. MTA2034 consists of the combination of 4 different main materials. Homogeneity of the dough is controlled by the computer system throughout the whole production process. Under these circumstances, glass seal dough does not affect the process variation.

The melting temperature of the dough from which the door glass seal is produced is a factor that may have an effect on the flexibility of the product.

Glass seal was developed by the R&D department of the company in accordance with the customer requests. The company has the authorization to modify the design. Six Sigma team determined that the profile dimensions, especially the wall thickness may affect the process variation.

Experience and education levels of the personnel are suitable for the operation. No evidence or complaint regarding the concentration of the personnel is present. Therefore, this subject cannot be considered as a factor affecting the process.

Production and inspection templates are regularly controlled by computer systems. On the other hand, maintenance operations are performed by the maintenance department on a routine basis.

The dough is produced in the automated, computer-controlled mixing unit with no errors. The mixtures of the formulas are prepared in three mixers with a 145-liter capacity and online filters.

The cooling time of the dough is an important factor affecting the flexibility quality characteristic of the door glass seal. Fast cooling time may cause a reduced flexibility of the glass seal.

Molds are regularly maintained by the maintenance department. The maintenance records are tracked on the computer system. Six Sigma team had the molds re-inspected. No nonconformities were detected following the inspection.

The temperature of the molds is another factor affecting the flexibility quality characteristic of the door glass seals.

The injection pressure of the rubber dough is also considered as a factor affecting the flexibility quality characteristic of the door glass seals.

Rubber production machines and equipment are regularly calibrated by accredited companies. Monthly controls and maintenance operations are conducted by the maintenance department as well.

Injection speed is also one of the significant factors affecting the flexibility quality characteristic of the door glass seals.

Dough mixtures are stored in cold storage facilities with a 300-ton capacity following production in order to prevent the weather and environmental conditions from affecting the product. Storage is operated with the First-in, First-out principle. All process steps from entry to the exit from storage are controlled by the computer system. Dough mixtures are consumed in ten days in average.

Six Sigma team combined the findings acquired through brainstorming and the detailed examination of the Ishikawa diagram with the information obtained from the R&D department and determined the factors considered to be affecting the flexibility quality characteristic of the door glass seals. Through these factors are:

- Cooling time.

- Injection pressure.
- Injection speed.
- Melting temperature.
- Mold temperature.
- Wall thickness.

The levels of these factors are determined by the R&D department. Each factor and the levels thereof affecting the flexibility quality characteristic are shown in Table 3.6.

Table 3.6 Factors affecting the flexibility of the glass seals

Factor Knowledge			Level		
Code	Control factor	Unit	1	2	3
A	Cooling time	Sec.	5	10	15
B	Injection pressure	Bar	250	450	650
C	Injection speed	cm/s	5	10	15
D	Melt Temperature	°C	470	480	490
E	Mold Temperature	°C	150	155	160
F	Wall Thickness	mm	2.10	2.15	2.20

In this phase, factors and the levels thereof causing the process variation are defined, which are $A_2B_2C_1D_2E_1F_1$ and highlighted with blue color in Table 3.6. According to Chen & Brahma (2014), “the most important part of the analyze phase is to identify the potential factors (X) that affect the project index (Y)” (p. 180).

3.5.4 Improve Phase

The levels of critical factors leading to process changes are determined and verified in this stage. In the improvement phase, the goal is to narrow down the gap between the current state of the process and the target value. Project management and other planning and administrative tools are utilized to introduce and enforce the new approach. Statistical techniques are implemented to confirm the enhancements (Pyzdek, 2003).

Taguchi method is widely used in phase to improve process or product. “Taguchi is a statistics method that aims to understand variation instead of conducting many experiments and is used to provide experiment runs” (Chen & Brahma, 2014, p. 181).

The factors and their levels affecting the flexibility of the front door glass seal in the current condition are defined as $A_2B_2C_1D_2E_1F_1$. The purpose of Six Sigma team to determine the optimal factors and their levels to eliminate the flexibility problem of the front door glass seal.

Factorial and fractional factorial experiments may necessitate a large number of experimental units, and therefore it may be reasonable to use one or more of the methods for the control of haphazard variation (Cox & Reid, 2000).

In this thesis implementation, a full factorial experiment design would need $3^6=729$ experiments. Since experiments are to be conducted with ten repetitions each for the average and the variance to be calculated effectively, there would be a total of 7,290 various experiments to perform. This enormous amount of experiments would increase the cost and cause time loss. Therefore, Six Sigma team decided to apply the Taguchi experiment design, which allows obtaining the optimal result by performing fewer experiments.

Taguchi (1987) takes concern in experiments generally to estimation the main effects, trying the meaning level based on the experiences of the experimenter. These experiments are not based on the potential trial combinations as a whole but rather on the examination of a fraction by using the vertical columns, triangular tables and linear graphs (Derviřođlu & Muluk, 2007). “The goal of the Taguchi method is to find control factor settings that generate acceptable responses despite natural environmental and process variability” (Proust, 2014, p. 311). In this study, a vertical column was formed in the 3^k system by using the Graeco-Latin Squares stemming from the Latin Squares method. It was determined by using the Graeco-Latin Squares method that the most suitable orthogonal array for six factors and three levels is L_{27} . Therefore, 27 individual experiments along with ten repetitions each, a total of 270

experiments were performed. As a result of the Taguchi experiment design, the total amount of experiments to be conducted went down by 7,020 - 96.29% - in comparison with the full factorial experiment design. *L27* Orthogonal experiment array obtained through Graeco-Latin Squares method is shown in Table 3.7.

Table 3.7 Suitable orthogonal arrays OA (27, 3⁶)

Experiment No	FACTORS											
	A	B	C	D	E	F	Cooling Time (A)	Injection Pressure (B)	Injection Speed (C)	Melt Temperature (D)	Mold Temperature (E)	Wall Thickness (F)
1	1	1	1	1	1	1	5	250	5	470	150	2.10
2	1	1	1	1	2	2	5	250	5	470	155	2.15
3	1	1	1	1	3	3	5	250	5	470	160	2.20
4	1	2	2	2	1	1	5	450	10	480	150	2.10
5	1	2	2	2	2	2	5	450	10	480	155	2.15
6	1	2	2	2	3	3	5	450	10	480	160	2.20
7	1	3	3	3	1	1	5	650	15	490	150	2.10
8	1	3	3	3	2	2	5	650	15	490	155	2.15
9	1	3	3	3	3	3	5	650	15	490	160	2.20
10	2	1	2	3	1	2	10	250	10	490	150	2.15
11	2	1	2	3	2	3	10	250	10	490	155	2.20
12	2	1	2	3	3	1	10	250	10	490	160	2.10
13	2	2	3	1	1	2	10	450	15	470	150	2.15
14	2	2	3	1	2	3	10	450	15	470	155	2.20
15	2	2	3	1	3	1	10	450	15	470	160	2.10
16	2	3	1	2	1	2	10	650	5	480	150	2.15
17	2	3	1	2	2	3	10	650	5	480	155	2.20
18	2	3	1	2	3	1	10	650	5	480	160	2.10
19	3	1	3	2	1	3	15	250	15	480	150	2.20
20	3	1	3	2	2	1	15	250	15	480	155	2.10
21	3	1	3	2	3	2	15	250	15	480	160	2.15
22	3	2	1	3	1	3	15	450	5	490	150	2.20
23	3	2	1	3	2	1	15	450	5	490	155	2.10
24	3	2	1	3	3	2	15	450	5	490	160	2.15
25	3	3	2	1	1	3	15	650	10	470	150	2.20
26	3	3	2	1	2	1	15	650	10	470	155	2.10
27	3	3	2	1	3	2	15	650	10	470	160	2.15

Adjustments on the factors affecting the flexibility, which triggered the customer complaint and their levels might also affect the following quality characteristics of the front door glass seal

- view (appearance),
- weight and
- hardness

ABC car manufacturer considers all of the quality characteristics i.e. response variables equally important.

Since all of the quality characteristics are ‘nominal is best’, the following formula was used to calculate the signal to noise ratio.

$$L_{ij} = k_3 \left(\frac{s^2}{\bar{y}_{ij}^2} \right) \quad (3.10)$$

L_{ij} = Quality loss for i^{th} response at j^{th} trial.

L_{ijk} = Observed data for i^{th} response at j^{th} trial, k^{th} repetition.

n_i = Replications for i^{th} response.

$$\bar{y}_{ij} = \frac{1}{n_i} \sum_{k=1}^{n_i} (y_{ijk}) \quad (3.11)$$

$$s_{ij} = \frac{1}{n_i - 1} \sum_{k=1}^{n_i} (y_{ijk} - \bar{y}_{ij})^2 \quad (3.12)$$

k_1, k_2, k_3 = Quality loss coefficients

The four responses (in order of importance) are:

- ✓ Flexibility, in which the target value is 9 ± 2 Newton;
- ✓ View, in which the target value is 1;
- ✓ Weight, in which the target value is 321 ± 10 gr;
- ✓ Hardness, in which the target value is 65-70 Shore A.

In order to determine the multi-response signal to noise (MRSN) ratio, dropping the variability needs normalizing the scale of the quality loss for each characteristic. Ratio of multi response S/N can be calculated by total normalized quality loss (TNQL). These three phases are (Tong, Su & Wang, 1997):

- Normalize the quality loss of each trial for each quality characteristics.

$$C_{ij} = \frac{L_{ij}}{L_i^*}, \quad \text{where } L_i^* = \max(L_{i1}, L_{i2}, \dots, L_{ij}) \quad (3.13)$$

- Calculate the total normalized quality loss (TNQL) of each trial.

$$TNQL_l = \sum_{i=1}^n w_i C_{ij} \quad (3.14)$$

Where w_i = the weight of the i th normalized response ($i = 1, 2, \dots, n$).

➤ Determine the optimal MRSN ratio for each trial:

$$MRSN_j = -10 \log(TNQL) \quad (3.15)$$

Taguchi experiment results were analyzed by taking response variables “flexibility, view, weight and hardness” quality characteristics into account.

The experiment numbers of response variables flexibility, view, weight and hardness and the results along with analyses of these experiments are demonstrated in Tables 3.8, 3.9, 3.10 and 3.11 respectively.



Table 3.8 Signal/noise results for flexibility

Experiment No	FACTORS						Replication for Flexibility										Flexibility			
	A	B	C	D	E	F	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	Mean	Variance	$L_{ij} = \frac{s^2}{\bar{y}^2}$	$C_{ij} = \frac{L_{ij}}{L_i^*}$
1	1	1	1	1	1	1	6.97	7.14	7.14	7.07	7.06	7.16	7.01	7.01	6.88	6.91	7.04	0.0094	0.00019	0.26731
2	1	1	1	1	2	2	8.95	8.96	9.00	8.73	8.86	9.07	8.82	8.87	8.82	8.98	8.91	0.0106	0.00013	0.18766
3	1	1	1	1	3	3	10.32	10.52	10.37	10.33	10.53	10.56	10.56	10.40	10.29	10.38	10.43	0.0112	0.00010	0.14441
4	1	2	2	2	1	1	7.13	6.95	6.90	7.12	7.10	6.90	7.01	6.95	6.97	7.13	7.02	0.0091	0.00018	0.25921
5	1	2	2	2	2	2	8.86	9.02	9.02	8.98	8.96	8.83	8.86	8.92	8.95	8.87	8.93	0.0048	0.00006	0.08513
6	1	2	2	2	3	3	10.46	10.52	10.26	10.20	10.32	10.21	10.35	10.38	10.44	10.51	10.37	0.0138	0.00013	0.18104
7	1	3	3	3	1	1	7.16	7.17	7.03	7.16	7.17	7.14	7.02	6.87	7.00	7.12	7.08	0.0101	0.00020	0.28228
8	1	3	3	3	2	2	8.75	8.89	8.78	8.73	8.98	8.69	8.85	8.83	8.88	8.83	8.82	0.0074	0.00010	0.13395
9	1	3	3	3	3	3	10.36	10.53	10.42	10.55	10.51	10.54	10.62	10.37	10.34	10.31	10.46	0.0115	0.00011	0.14848
10	2	1	2	3	1	2	8.75	8.81	8.87	8.91	8.90	8.85	8.94	8.87	8.81	9.03	8.87	0.0061	0.00008	0.10884
11	2	1	2	3	2	3	10.22	10.22	10.39	10.39	10.44	10.42	10.21	10.22	10.43	10.46	10.34	0.0116	0.00011	0.15202
12	2	1	2	3	3	1	7.20	6.96	7.02	7.05	7.09	7.06	7.01	7.13	7.59	7.34	7.15	0.0363	0.00071	1.00000
13	2	2	3	1	1	2	9.02	8.87	8.88	8.90	9.11	8.98	8.81	8.91	8.84	8.86	8.92	0.0085	0.00011	0.15006
14	2	2	3	1	2	3	10.45	10.17	10.50	10.24	10.52	10.25	10.46	10.35	10.25	10.32	10.35	0.0154	0.00014	0.20259
15	2	2	3	1	3	1	7.18	7.06	7.14	7.12	7.16	7.10	7.27	7.26	6.89	7.20	7.14	0.0120	0.00023	0.33054
16	2	3	1	2	1	2	8.76	8.69	8.74	8.76	8.65	8.87	8.71	8.79	8.78	8.82	8.76	0.0041	0.00005	0.07502
17	2	3	1	2	2	3	10.57	10.39	10.55	10.28	10.39	10.16	10.21	10.33	10.45	10.23	10.36	0.0196	0.00018	0.25741
18	2	3	1	2	3	1	6.99	7.12	7.32	7.10	7.29	7.04	7.13	7.01	7.01	7.21	7.12	0.0139	0.00027	0.38502
19	3	1	3	2	1	3	10.46	10.21	10.22	10.46	10.21	10.23	10.39	10.34	10.26	10.12	10.29	0.0135	0.00013	0.17919
20	3	1	3	2	2	1	7.36	7.25	7.30	7.35	7.06	7.11	6.86	7.31	7.37	7.20	7.22	0.0269	0.00052	0.72618
21	3	1	3	2	3	2	8.94	8.82	8.75	8.82	8.81	8.61	8.73	8.70	8.78	8.83	8.78	0.0079	0.00010	0.14375
22	3	2	1	3	1	3	10.35	10.06	10.20	10.11	10.28	10.11	10.37	10.29	10.14	10.06	10.20	0.0139	0.00013	0.18760
23	3	2	1	3	2	1	7.13	7.08	7.32	7.15	7.32	6.93	7.32	7.21	7.33	7.31	7.21	0.0184	0.00035	0.49907
24	3	2	1	3	3	2	8.75	8.75	8.77	8.85	8.88	8.79	8.73	8.66	8.62	8.71	8.75	0.0062	0.00008	0.11406
25	3	3	2	1	1	3	10.39	10.28	10.10	10.37	10.35	10.11	10.13	10.16	10.13	10.25	10.23	0.0132	0.00013	0.17723
26	3	3	2	1	2	1	6.98	6.94	7.00	6.99	7.12	7.31	7.38	7.21	7.02	7.20	7.12	0.0235	0.00046	0.65218
27	3	3	2	1	3	2	9.04	8.88	8.94	8.86	8.85	8.92	9.00	8.97	8.83	8.81	8.91	0.0059	0.00007	0.10434

Table 3.9 Signal/noise results for view

Experiment No	FACTORS						Replication for View										View			
	A	B	C	D	E	F	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	Mean	Variance	$L_{ij} = \frac{s^2}{\bar{y}^2}$	$C_{ij} = \frac{L_{ij}}{L_i^*}$
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1.00	0.00000	0.00000	0.00000
2	1	1	1	1	2	2	1	1	1	1	1	1	1	1	1	1	1.00	0.00000	0.00000	0.00000
3	1	1	1	1	3	3	1	1	1	1	1	1	1	1	1	1	1.00	0.00000	0.00000	0.00000
4	1	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1.00	0.00000	0.00000	0.00000
5	1	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1.00	0.00000	0.00000	0.00000
6	1	2	2	2	3	3	1	1	1	1	1	1	1	1	0	1	0.90	0.10000	0.12346	0.16667
7	1	3	3	3	1	1	1	1	1	1	1	1	1	1	1	1	1.00	0.00000	0.00000	0.00000
8	1	3	3	3	2	2	1	1	1	1	1	1	1	1	1	1	1.00	0.00000	0.00000	0.00000
9	1	3	3	3	3	3	0	1	1	0	0	1	1	1	1	0	0.60	0.26667	0.74074	1.00000
10	2	1	2	3	1	2	1	1	1	1	1	1	1	1	1	1	1.00	0.00000	0.00000	0.00000
11	2	1	2	3	2	3	1	1	1	1	1	1	1	1	1	1	1.00	0.00000	0.00000	0.00000
12	2	1	2	3	3	1	1	1	1	1	1	1	1	1	1	1	1.00	0.00000	0.00000	0.00000
13	2	2	3	1	1	2	1	1	1	1	1	1	1	1	1	1	1.00	0.00000	0.00000	0.00000
14	2	2	3	1	2	3	1	1	1	1	1	1	1	1	1	1	1.00	0.00000	0.00000	0.00000
15	2	2	3	1	3	1	1	1	1	1	1	1	1	1	1	1	1.00	0.00000	0.00000	0.00000
16	2	3	1	2	1	2	1	1	1	1	1	1	1	1	1	1	1.00	0.00000	0.00000	0.00000
17	2	3	1	2	2	3	1	1	1	1	1	1	1	1	1	1	1.00	0.00000	0.00000	0.00000
18	2	3	1	2	3	1	1	1	1	1	1	1	1	1	1	1	1.00	0.00000	0.00000	0.00000
19	3	1	3	2	1	3	1	1	1	1	1	1	1	1	1	1	1.00	0.00000	0.00000	0.00000
20	3	1	3	2	2	1	1	1	1	1	1	1	1	1	1	1	1.00	0.00000	0.00000	0.00000
21	3	1	3	2	3	2	1	1	1	1	1	1	1	1	1	1	1.00	0.00000	0.00000	0.00000
22	3	2	1	3	1	3	1	1	1	1	1	1	1	1	1	1	1.00	0.00000	0.00000	0.00000
23	3	2	1	3	2	1	1	1	1	1	1	1	1	1	1	1	1.00	0.00000	0.00000	0.00000
24	3	2	1	3	3	2	1	1	1	1	1	1	1	1	1	1	1.00	0.00000	0.00000	0.00000
25	3	3	2	1	1	3	1	1	1	1	1	1	1	1	1	1	1.00	0.00000	0.00000	0.00000
26	3	3	2	1	2	1	1	1	1	1	1	1	1	1	1	1	1.00	0.00000	0.00000	0.00000
27	3	3	2	1	3	2	1	1	1	1	1	1	1	1	1	1	1.00	0.00000	0.00000	0.00000

Table 3.10 Signal/noise results for weight

Experiment No	FACTORS						Replication for Weight										Weight			
	A	B	C	D	E	F	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	Mean	Variance	$L_{ij} = \frac{s^2}{\bar{y}^2}$	$C_{ij} = \frac{L_{ij}}{L_i^*}$
1	1	1	1	1	1	1	316.7	317.1	315.1	315.8	315.9	315.9	315.8	316.1	315.8	315.6	315.97	0.3280	0.0000033	0.66181
2	1	1	1	1	2	2	320.3	319.7	319.9	320.1	319.8	321.0	320.1	319.6	320.2	320.0	320.06	0.1574	0.0000015	0.30941
3	1	1	1	1	3	3	325.6	325.8	325.6	324.5	324.7	324.5	324.7	324.9	324.6	324.6	324.95	0.2547	0.0000024	0.48593
4	1	2	2	2	1	1	314.9	315.7	315.6	316.1	316.4	315.5	316.8	316.4	316.2	316.1	315.97	0.2949	0.0000030	0.59491
5	1	2	2	2	2	2	320.3	320.4	320.4	319.2	320.1	319.5	320.0	319.9	320.1	319.8	319.98	0.1528	0.0000015	0.30062
6	1	2	2	2	3	3	324.6	324.7	324.2	325.3	324.5	325.5	325.4	323.9	324.8	324.7	324.75	0.2544	0.0000024	0.48591
7	1	3	3	3	1	1	315.1	316.3	315.5	316.4	315.8	315.9	316.1	316.2	316.0	316.7	316.00	0.2055	0.0000021	0.41453
8	1	3	3	3	2	2	320.4	319.9	320.5	320.5	320.4	319.8	320.5	319.9	319.7	320.8	320.23	0.1402	0.0000014	0.27546
9	1	3	3	3	3	3	324.3	325.3	324.3	324.3	325.5	324.7	324.9	324.4	325.0	325.5	324.82	0.2396	0.0000023	0.45744
10	2	1	2	3	1	2	319.9	320.3	320.5	320.1	319.7	320.1	319.4	320.1	320.2	320.4	320.07	0.1129	0.0000011	0.22198
11	2	1	2	3	2	3	324.1	324.7	325.8	324.7	324.5	325.4	323.6	323.9	324.5	324.2	324.54	0.4495	0.0000043	0.85963
12	2	1	2	3	3	1	314.6	316.2	316.5	316.4	316.4	316.0	315.5	315.1	315.3	316.7	315.88	0.4954	0.0000050	1.00000
13	2	2	3	1	1	2	320.1	319.9	320.4	320.5	320.0	320.1	320.1	319.1	319.8	320.1	320.00	0.1382	0.0000013	0.27174
14	2	2	3	1	2	3	324.2	324.2	324.6	324.0	325.1	324.7	324.3	325.3	325.2	324.3	324.57	0.2064	0.0000020	0.39468
15	2	2	3	1	3	1	316.2	316.1	316.2	315.2	314.8	316.2	317.2	315.6	315.6	316.4	315.95	0.4564	0.0000046	0.92091
16	2	3	1	2	1	2	319.9	320.1	320.4	320.1	320.0	319.7	320.4	320.3	320.2	320.1	320.11	0.0468	0.0000005	0.09192
17	2	3	1	2	2	3	325.1	324.6	324.6	324.8	324.4	325.6	324.0	324.3	324.7	325.6	324.75	0.2717	0.0000026	0.51892
18	2	3	1	2	3	1	316.6	316.8	316.0	315.5	315.3	316.3	316.5	316.1	316.6	316.3	316.18	0.2418	0.0000024	0.48712
19	3	1	3	2	1	3	324.1	325.5	324.4	325.4	324.5	325.2	325.5	325.0	325.3	325.2	324.99	0.2581	0.0000024	0.49215
20	3	1	3	2	2	1	315.4	316.3	315.7	315.7	316.7	315.3	316.4	316.8	315.5	316.7	316.06	0.3542	0.0000035	0.71430
21	3	1	3	2	3	2	320.2	319.9	320.3	320.3	319.7	320.2	320.0	320.7	319.6	320.7	320.15	0.1345	0.0000013	0.26432
22	3	2	1	3	1	3	325.7	325.8	325.4	325.8	325.2	325.7	325.9	325.8	325.6	326.5	325.74	0.1168	0.0000011	0.22180
23	3	2	1	3	2	1	315.1	315.7	315.4	316.3	316.4	315.7	316.1	316.4	316.1	316.1	315.93	0.1875	0.0000019	0.37838
24	3	2	1	3	3	2	319.8	320.3	320.6	320.3	320.2	320.2	320.3	320.6	320.3	320.5	320.29	0.0536	0.0000005	0.10520
25	3	3	2	1	1	3	324.8	324.8	325.2	325.5	325.2	324.0	324.7	325.4	324.7	324.4	324.87	0.2254	0.0000021	0.43017
26	3	3	2	1	2	1	316.8	316.6	316.6	315.8	314.9	316.0	315.8	315.2	316.5	316.7	316.07	0.4436	0.0000044	0.89434
27	3	3	2	1	3	2	320.0	319.5	320.3	320.2	320.4	319.8	319.9	319.7	320.1	320.6	320.07	0.1128	0.0000011	0.22171

Table 3.11. Signal/noise results for hardness

Experiment No	FACTORS						Replication for Hardness										Hardness			
	A	B	C	D	E	F	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	Mean	Variance	$L_{ij} = \frac{s^2}{\bar{y}^2}$	$C_{ij} = \frac{L_{ij}}{L_i^*}$
1	1	1	1	1	1	1	65.90	66.44	66.13	66.35	66.52	66.31	66.40	66.22	66.10	66.24	66.26	0.0338	0.0000077	0.91695
2	1	1	1	1	2	2	67.27	67.10	67.09	67.10	67.07	67.03	67.08	67.09	66.97	67.12	67.09	0.0058	0.0000013	0.15272
3	1	1	1	1	3	3	68.24	68.23	68.01	67.89	68.17	68.03	68.23	68.09	68.17	67.95	68.10	0.0159	0.0000034	0.40763
4	1	2	2	2	1	1	66.33	66.39	66.57	66.25	66.41	66.38	66.33	66.09	66.30	65.87	66.29	0.0369	0.0000084	1.00000
5	1	2	2	2	2	2	67.13	67.22	67.08	67.16	67.19	67.19	67.17	67.21	67.11	67.08	67.15	0.0026	0.0000006	0.06994
6	1	2	2	2	3	3	68.06	68.04	68.21	68.04	68.23	67.98	68.18	68.20	68.09	68.14	68.12	0.0075	0.0000016	0.19222
7	1	3	3	3	1	1	66.33	66.09	66.28	66.38	66.33	66.17	66.21	66.41	66.32	66.33	66.29	0.0099	0.0000022	0.26755
8	1	3	3	3	2	2	67.12	67.10	67.19	67.11	67.28	67.15	67.19	67.22	67.12	67.18	67.17	0.0032	0.0000007	0.08575
9	1	3	3	3	3	3	67.96	68.03	68.08	68.11	67.94	68.17	68.09	67.93	67.95	68.00	68.03	0.0069	0.0000015	0.17795
10	2	1	2	3	1	2	67.11	67.16	67.18	67.21	67.15	67.20	67.23	67.16	67.15	67.26	67.18	0.0020	0.0000004	0.05186
11	2	1	2	3	2	3	68.19	68.13	68.08	67.98	68.06	68.08	68.11	68.08	68.10	68.11	68.09	0.0028	0.0000006	0.07282
12	2	1	2	3	3	1	66.28	66.30	66.36	66.31	66.31	66.23	66.29	66.18	66.09	66.53	66.29	0.0132	0.0000030	0.35879
13	2	2	3	1	1	2	67.21	67.25	67.20	67.11	67.11	67.13	67.09	67.11	67.10	67.21	67.15	0.0034	0.0000008	0.09084
14	2	2	3	1	2	3	68.06	68.02	67.99	68.11	68.07	68.09	67.93	68.06	68.03	67.98	68.03	0.0030	0.0000007	0.07843
15	2	2	3	1	3	1	66.37	66.30	66.22	66.36	66.39	66.12	66.40	66.41	66.12	66.28	66.30	0.0122	0.0000028	0.33175
16	2	3	1	2	1	2	67.19	67.13	67.17	67.32	67.16	67.18	67.13	67.15	67.16	67.11	67.17	0.0034	0.0000007	0.08915
17	2	3	1	2	2	3	68.06	68.20	68.16	68.05	68.10	68.21	68.13	68.17	68.06	68.03	68.12	0.0044	0.0000009	0.11180
18	2	3	1	2	3	1	66.37	66.34	66.28	66.37	66.46	66.25	66.33	66.25	66.38	66.41	66.34	0.0047	0.0000011	0.12757
19	3	1	3	2	1	3	68.05	67.94	68.22	68.05	68.13	68.11	68.06	68.03	68.08	67.98	68.07	0.0061	0.0000013	0.15721
20	3	1	3	2	2	1	66.26	66.23	66.37	66.26	66.32	66.23	66.32	66.35	66.21	66.15	66.27	0.0048	0.0000011	0.12894
21	3	1	3	2	3	2	67.20	67.21	67.13	67.20	67.17	67.06	67.19	67.15	67.06	67.14	67.15	0.0030	0.0000007	0.08007
22	3	2	1	3	1	3	68.10	68.16	68.11	68.01	68.07	67.96	68.11	67.98	68.01	67.96	68.05	0.0052	0.0000011	0.13261
23	3	2	1	3	2	1	66.27	66.22	66.40	66.29	66.17	66.34	66.20	66.38	66.19	66.31	66.28	0.0066	0.0000015	0.17834
24	3	2	1	3	3	2	67.19	67.03	67.14	67.11	67.15	67.05	67.17	67.15	67.11	67.05	67.12	0.0031	0.0000007	0.08063
25	3	3	2	1	1	3	68.10	68.10	67.96	68.12	67.98	68.06	67.99	68.22	68.23	68.02	68.08	0.0090	0.0000019	0.23112
26	3	3	2	1	2	1	66.29	66.27	66.43	66.34	66.23	66.34	66.13	66.43	66.37	66.38	66.32	0.0087	0.0000020	0.23670
27	3	3	2	1	3	2	67.16	67.15	67.08	67.16	67.19	67.04	67.02	67.15	67.13	67.15	67.12	0.0032	0.0000007	0.08460

As shown below, the total normalized quality loss (TNQL) of each trial is calculated:

$$TNQL_1 = w_1C_{11} + w_2C_{21} + w_3C_{31} + w_4C_{41} \quad (3.16)$$

$$TNQL_1 = 1 * 0.26731 + 1 * 0.00000 + 1 * 0.66181 + 1 * 0.91695$$

$$TNQL_1 = 1.84607$$

$$TNQL_2 = w_1C_{12} + w_2C_{22} + w_3C_{32} + w_4C_{42} \quad (3.17)$$

$$TNQL_2 = 1 * 0.18766 + 1 * 0.00000 + 1 * 0.30941 + 1 * 0.15272$$

$$TNQL_2 = 0.64979$$

Similarly, the total normalized quality loss (TNQL) of each trial is calculated. Table 3.12 shows the calculation results.

Following the calculation of $TNQL$, the multi-response signal to noise ratio (MRSN) is computed with the equation given below.

$$MRSN_j = -10\log(TNQL) \quad (3.18)$$

For each trial, optimum factor levels were determined by calculating the multi-response signal/noise ratio.

$$MRSN_1 = -10 \log(TNQL_1) = -10 \log(1.84607) = -2.66248 \quad (3.19)$$

$$MRSN_2 = -10 \log(TNQL_2) = -10 \log(0.64980) = 1.87220 \quad (3.20)$$

Multi response signal/noise ratio of all these trials are shown in Table 3.12.

Table 3.12 Data summary by experiment

Experiment No	FACTORS						FACTORS						$TNQL_j$ $= \sum_{i=1}^n w_i C_{ij}$	$MRSN_j$ $= -10\log(TNQL)$
	A	B	C	D	E	F	Cooling Time (A)	Injection Pressure (B)	Injection Speed (C)	Melt Temperature (D)	Mold Temperature (E)	Wall Thickness (F)		
1	1	1	1	1	1	1	5	250	5	470	150	2.10	1.84607	-2.66248
2	1	1	1	1	2	2	5	250	5	470	155	2.15	0.64980	1.87222
3	1	1	1	1	3	3	5	250	5	470	160	2.20	1.03797	-0.16187
4	1	2	2	2	1	1	5	450	10	480	150	2.10	1.85412	-2.68137
5	1	2	2	2	2	2	5	450	10	480	155	2.15	0.45569	3.41327
6	1	2	2	2	3	3	5	450	10	480	160	2.20	1.02584	-0.11078
7	1	3	3	3	1	1	5	650	15	490	150	2.10	0.96436	0.15761
8	1	3	3	3	2	2	5	650	15	490	155	2.15	0.49517	3.05246
9	1	3	3	3	3	3	5	650	15	490	160	2.20	1.78387	-2.51363
10	2	1	2	3	1	2	10	250	10	490	150	2.15	0.38267	4.17175
11	2	1	2	3	2	3	10	250	10	490	155	2.20	1.08447	-0.35219
12	2	1	2	3	3	1	10	250	10	490	160	2.10	2.35879	-3.72689
13	2	2	3	1	1	2	10	450	15	470	150	2.15	0.51263	2.90192
14	2	2	3	1	2	3	10	450	15	470	155	2.20	0.67571	1.70242
15	2	2	3	1	3	1	10	450	15	470	160	2.10	1.58320	-1.99536
16	2	3	1	2	1	2	10	650	5	480	150	2.15	0.25608	5.91621
17	2	3	1	2	2	3	10	650	5	480	155	2.20	0.88814	0.51520
18	2	3	1	2	3	1	10	650	5	480	160	2.10	0.99972	0.00122
19	3	1	3	2	1	3	15	250	15	480	150	2.20	0.82855	0.81683
20	3	1	3	2	2	1	15	250	15	480	155	2.10	1.56942	-1.95738
21	3	1	3	2	3	2	15	250	15	480	160	2.15	0.48814	3.11456
22	3	2	1	3	1	3	15	450	5	490	150	2.20	0.54201	2.65996
23	3	2	1	3	2	1	15	450	5	490	155	2.10	1.05578	-0.23574
24	3	2	1	3	3	2	15	450	5	490	160	2.15	0.29989	5.23035
25	3	3	2	1	1	3	15	650	10	470	150	2.20	0.83852	0.76486
26	3	3	2	1	2	1	15	650	10	470	155	2.10	1.78322	-2.51206
27	3	3	2	1	3	2	15	650	10	470	160	2.15	0.41065	3.86526

Each factor and the effects of their respective levels are computed with following calculation of MRSN values. Calculation method and results are as follows (Nahas, 2012).

Effect values of the “A” factor levels:

$$S/N_{A1} = \frac{\eta_1 + \eta_2 + \eta_3 + \eta_4 + \eta_5 + \eta_6 + \eta_7 + \eta_8 + \eta_9}{9} = 0.041 \quad (3.21)$$

$$S/N_{A2} = \frac{\eta_{10} + \eta_{11} + \eta_{12} + \eta_{13} + \eta_{14} + \eta_{15} + \eta_{16} + \eta_{17} + \eta_{18}}{9} = 1.015 \quad (3.22)$$

$$S/N_{A3} = \frac{\eta_{19} + \eta_{20} + \eta_{21} + \eta_{22} + \eta_{23} + \eta_{24} + \eta_{25} + \eta_{26} + \eta_{27}}{9} = 1.305 \quad (3.23)$$

Effect values of the “B” factor levels:

$$S/N_{B1} = \frac{\eta_1 + \eta_2 + \eta_3 + \eta_{10} + \eta_{11} + \eta_{12} + \eta_{19} + \eta_{20} + \eta_{21}}{9} = 0.124 \quad (3.24)$$

$$S/N_{B2} = \frac{\eta_4 + \eta_5 + \eta_6 + \eta_{13} + \eta_{14} + \eta_{15} + \eta_{22} + \eta_{23} + \eta_{24}}{9} = 1.209 \quad (3.25)$$

$$S/N_{B3} = \frac{\eta_7 + \eta_8 + \eta_9 + \eta_{16} + \eta_{17} + \eta_{18} + \eta_{25} + \eta_{26} + \eta_{27}}{9} = 1.027 \quad (3.26)$$

Effect values of the “C” factor levels:

$$S/N_{C1} = \frac{\eta_1 + \eta_2 + \eta_{31} + \eta_{16} + \eta_{17} + \eta_{18} + \eta_{22} + \eta_{23} + \eta_{24}}{9} = 1.459 \quad (3.27)$$

$$S/N_{C2} = \frac{\eta_4 + \eta_5 + \eta_6 + \eta_{10} + \eta_{11} + \eta_{12} + \eta_{25} + \eta_{26} + \eta_{27}}{9} = 0.315 \quad (3.28)$$

$$S/N_{C3} = \frac{\eta_7 + \eta_8 + \eta_9 + \eta_{13} + \eta_{14} + \eta_{15} + \eta_{19} + \eta_{20} + \eta_{21}}{9} = 0.587 \quad (3.29)$$

Effect values of the “D” factor levels:

$$S/N_{D1} = \frac{\eta_1 + \eta_2 + \eta_{31} + \eta_{13} + \eta_{14} + \eta_{15} + \eta_{25} + \eta_{26} + \eta_{27}}{9} = 0.419 \quad (3.30)$$

$$S/N_{D2} = \frac{\eta_4 + \eta_5 + \eta_6 + \eta_{16} + \eta_{17} + \eta_{18} + \eta_{19} + \eta_{20} + \eta_{21}}{9} = 1.003 \quad (3.31)$$

$$S/N_{D3} = \frac{\eta_7 + \eta_8 + \eta_9 + \eta_{10} + \eta_{11} + \eta_{12} + \eta_{22} + \eta_{23} + \eta_{24}}{9} = 0.938 \quad (3.32)$$

Effect values of the “E” factor levels:

$$S/N_{E1} = \frac{\eta_1 + \eta_4 + \eta_7 + \eta_{10} + \eta_{13} + \eta_{16} + \eta_{19} + \eta_{22} + \eta_{25}}{9} = 1.338 \quad (3.33)$$

$$S/N_{E2} = \frac{\eta_2 + \eta_5 + \eta_8 + \eta_{11} + \eta_{14} + \eta_{17} + \eta_{20} + \eta_{23} + \eta_{26}}{9} = 0.611 \quad (3.34)$$

$$S/N_{E3} = \frac{\eta_3 + \eta_6 + \eta_9 + \eta_{12} + \eta_{15} + \eta_{18} + \eta_{21} + \eta_{24} + \eta_{27}}{9} = 0.411 \quad (3.35)$$

Effect values of the “F” factor levels:

$$S/N_{F1} = \frac{\eta_1 + \eta_4 + \eta_7 + \eta_{12} + \eta_{15} + \eta_{18} + \eta_{20} + \eta_{23} + \eta_{26}}{9} = -1.735 \quad (3.36)$$

$$S/N_{F2} = \frac{\eta_2 + \eta_5 + \eta_8 + \eta_{10} + \eta_{13} + \eta_{16} + \eta_{21} + \eta_{24} + \eta_{27}}{9} = 3.726 \quad (3.37)$$

$$S/N_{F3} = \frac{\eta_3 + \eta_6 + \eta_9 + \eta_{11} + \eta_{14} + \eta_{17} + \eta_{19} + \eta_{22} + \eta_{25}}{9} = 0.369 \quad (3.38)$$

The quality characteristics table by factor level for the

- cooling time,
- injection pressure,
- injection speed,
- melt temperature,
- mold temperature and
- wall thickness

was produced in the integrated manner and the outcomes are given in Table 3.13. Best levels are shown in blue color.

Table 3.13 S/N ratio value by factor level

Level	A	B	C	D	E	F
1	0.041	0.124	1.459	0.419	1.338	-1.735
2	1.015	1.209	0.315	1.003	0.611	3.726
3	1.305	1.027	0.587	0.938	0.411	0.369
Delta (Δ)	1.264	1.085	1.144	0.584	0.927	5.461
Rank	2	4	3	6	5	1

$$\Delta = \text{Maximum} - \text{Minimum} \quad (3.39)$$

In Figure 3.15, each factor and the levels thereof are shown in a diagram.

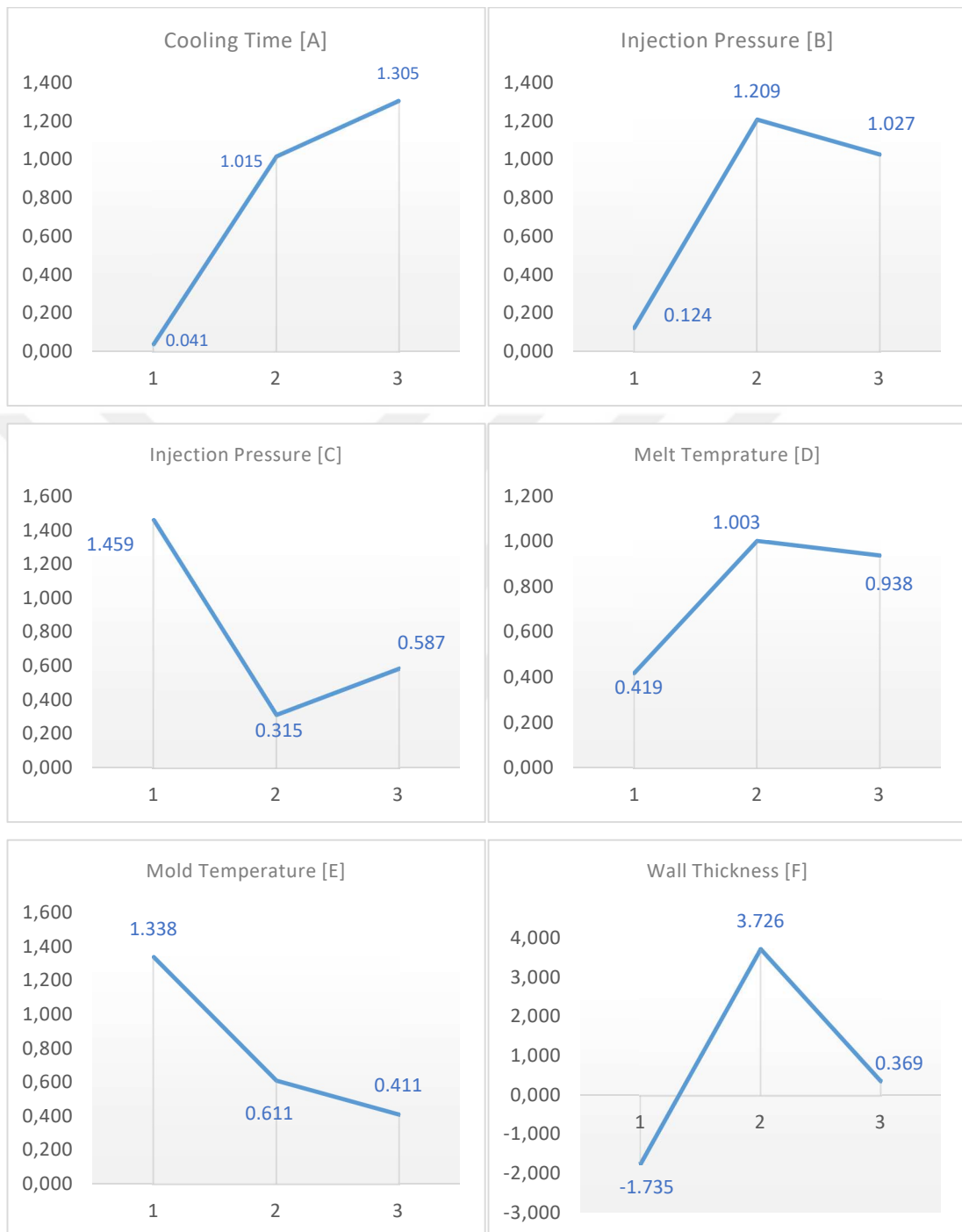


Figure 3.15 Main effects plots for S/N ratio value on factors

The optimal level combination is determined as $A_3B_2C_1D_2E_1F_2$, taking Figure 3.15 and Table 3.13 into consideration.

The percent numbers depict that cooling time, injection pressure, injection speed, melt temperature, mold temperature and wall thickness have significant effects on the flexibility, view, weight and hardness values. It can also be observed from Table 3.14.

Each factor has two degrees of freedom since all factors affecting the quality characteristics possess three levels.

$$df = \text{Number of level} - 1 = 3 - 1 = 2 \quad (3.40)$$

Table 3.14 Anova results for response variables

Source of Variation	Degree of Freedom	Sum of Square	Mean of Square	F-ratio	Percentage Contribution (P)
Cooling Time [A]	2	7.898	3.95	3.10487	4.365%
Injection Pressure [B]	2	6.084	3.04	2.39181	3.362%
Injection Speed [C]	2	6.439	3.22	2.53133	3.558%
Melt Temperature [D]	2	1.842	0.92	0.72407	1.018%
Mold Temperature [E]	2	4.285	2.14	1.68433	2.368%
Wall Thickness [F]	2	136.567	68.28	53.68642	75.483%
Error	14	17.807	1.27		9.842%
Total	26	180.922			100.0%

An F test is conducted to identify design parameters which has an important effect on the responses. As point out Oji, Sunday, Petinrin & Adetunji (2003), “in the analysis, the F-ratio is a ratio of the mean square error to the residual error, and is traditionally used to determine the significance of a factor” (p. 6).

ANOVA table was calculated as shown in the equations below.

$$SS_T = \sum_{i=1}^n (\eta_i - \eta_m)^2 = 180.922 \quad (3.41)$$

η_m : The total mean S/N ratio

η_i : The mean S/N ratio for i^{th} experiment

n : The number of experiments in the orthogonal array

$$\eta_m = \sum_{i=1}^n \frac{\eta_i}{n} = 0.78690 \quad (3.42)$$

As shown in the below equation, sum of squares for each factor are computed.

$$SS_A = 9(m_{A_1} - m)^2 + 9(m_{A_2} - m)^2 + 9(m_{A_3} - m)^2 \quad (3.43)$$

$$SS_A = 9(0.041 - 0.78690)^2 + 9(1.015 - 0.78690)^2 + 9(1.305 - 0.78690)^2$$

$$SS_A = 7.898$$

The sums of squares for the remaining factors are calculated (sum of squares–SS).

The results are as follows:

$$SS_B = 6.084$$

$$SS_C = 6.439$$

$$SS_D = 1.842$$

$$SS_E = 4.285$$

$$SS_F = 136.567$$

$$SS_e = 17.807$$

$$\text{Percentage Contribution } (P) = \frac{SS_{\text{Factor}}}{SS_{\text{Total}}} \quad (3.44)$$

Percentage contribution shows the contribution of each factor to the variation as the percentage. Following calculations are performed for each factor:

$$P_A = \frac{SS_A}{SS_{\text{Total}}} = \frac{7.898}{180.922} = 4.365\% \quad (3.45)$$

$$P_B = \frac{SS_B}{SS_{\text{Total}}} = 3.362\% \quad (3.46)$$

$$P_C = \frac{SS_C}{SS_{\text{Total}}} = 3.558\% \quad (3.47)$$

$$P_D = \frac{SS_D}{SS_{\text{Total}}} = 1.018\% \quad (3.48)$$

$$P_E = \frac{SS_E}{SS_{\text{Total}}} = 2.368\% \quad (3.49)$$

$$P_F = \frac{SS_F}{SS_{\text{Total}}} = 75.483\% \quad (3.50)$$

$$P_e = \frac{SS_e}{SS_{\text{Total}}} = 9.842\% \quad (3.51)$$

The most influential factor on the front door glass seal flexibility is the glass seal walls thickness factor, ‘F’ with a rate of 75.483%.

The optimum level combination “ $A_3B_2C_1D_2E_1F_2$ ” requires being confirmed. Verification was performed with the test of the optimum combination condition obtained through Taguchi experiment design. For this purpose, data pertaining to the

combination $A_3B_2C_1D_2E_1F_2$ was collected. Since the orthogonal array L_{27} was used in the project and experiments were performed with ten repetitions, 270 data sets are present. In order to verify the optimum combination $A_3B_2C_1D_2E_1F_2$ obtained through the multi response Taguchi experiment design, 30 verification experiments were performed. Results obtained through the experiment are shown in Table 3.15.

Table 3.15 Confirmation experiment results per response variable

A ₃ B ₂ C ₁ D ₂ E ₁ F ₂							
Flexibility		View		Weight		Hardness	
Experiment No	Value	Experiment No	Value	Experiment No	Value	Experiment No	Value
1	9.04	1	1	1	320.96	1	67.45
2	9.03	2	1	2	321.02	2	67.51
3	9.12	3	1	3	320.92	3	67.49
4	8.98	4	1	4	320.92	4	67.53
5	9.16	5	1	5	321.03	5	67.53
6	9.16	6	1	6	320.99	6	67.48
7	9.05	7	1	7	320.99	7	67.52
8	9.02	8	1	8	320.97	8	67.61
9	9.05	9	1	9	320.96	9	67.46
10	8.97	10	1	10	320.95	10	67.56
11	8.99	11	1	11	320.95	11	67.55
12	9.09	12	1	12	321.04	12	67.43
13	8.97	13	1	13	321.05	13	67.51
14	8.98	14	1	14	320.97	14	67.54
15	8.95	15	1	15	320.98	15	67.48
16	9.16	16	1	16	321.03	16	67.48
17	9.17	17	1	17	320.99	17	67.43
18	9.03	18	1	18	320.95	18	67.59
19	9.01	19	1	19	320.97	19	67.45
20	8.93	20	1	20	321.01	20	67.51
21	9.02	21	1	21	320.00	21	67.46
22	8.96	22	1	22	320.98	22	67.52
23	9.15	23	1	23	320.98	23	67.44
24	9.06	24	1	24	321.04	24	67.53
25	9.01	25	1	25	320.97	25	67.51
26	9.05	26	1	26	321.03	26	67.56
27	9.09	27	1	27	320.95	27	67.53
28	9.15	28	1	28	321.06	28	67.57
29	9.03	29	1	29	320.97	29	67.52
30	8.97	30	1	30	321.05	30	67.49

Defining statistical data regarding the standard deviation, variation and range of the initial condition ($A_2B_2C_1D_2E_1F_1$), ten best conditions and the optimum combination $A_3B_2C_1D_2E_1F_2$ obtained through Taguchi experiment design of the four quality characteristics are given in Table 3.16.

Table 3.16 Compare of confirmation data's with starting condition, best 10 condition, and optimum condition

Response Variables	Statistics	Starting Condition ($A_2B_2C_1D_2E_1F_1$)	Best 10	Optimum Condition ($A_3B_2C_1D_2E_1F_2$)
Flexibility	Average	8.768	9.133	9.045
	Std.Dev.	1.322	0.555	0.072
	Variance	1.748	0.308	0.005
	Range	3.760	1.800	0.240
View	Average	0.981	1.000	1.000
	Std.Dev.	0.135	0.000	0.000
	Variance	0.018	0.000	0.000
	Range	1.000	0.000	0.000
Weight	Average	320.331	320.668	320.956
	Std.Dev.	3.673	1.732	0.185
	Variance	13.492	2.999	0.034
	Range	11.900	7.370	1.060
Hardness	Average	67.171	67.235	67.508
	Std.Dev.	0.735	0.279	0.046
	Variance	0.540	0.078	0.002
	Range	2.370	1.190	0.180

As average, standard deviation, variation, and range data are given in Table 3.16 are examined, it can be clearly seen that an improvement in flexibility, view, weight and hardness quality characteristics. Therefore, it can be assumed that the combination $A_3B_2C_1D_2E_1F_2$ is suitable. Following the experiment, the average values were drawn closer to the nominal values.

Since average, standard deviation and variation values are significantly reduced as well; it is seen that the combination $A_3B_2C_1D_2E_1F_2$ is reasonable.

Table 3.17 According to normalized costs (C_{ij}) TNQL and MRSN values

Combination	Flexibility	View	Weight	Hardness	Flexibility	View	Weight	Hardness	1.0; 1.0; 1.0; 1.0		Improvement (dB)
	L1j	L2j	L3j	L4j	C1j	C2j	C3j	C4j	TNQL _j	MRSN _j	
Starting Condition (A ₂ B ₂ C ₁ D ₂ E ₁ F ₁)	0.0001879	0.0320073	0.0000023	0.0000011	1	1	1	1	4	-6.021	
Best 10 Condition	0.0000969	0.0000000	0.0000011	0.0000008	0.5156998	0	0.4782609	0.7272727	1.7212334	-2.358	3.663
Optimum Condition (A ₃ B ₂ C ₁ D ₂ E ₁ F ₂)	0.0000630	0.0000000	0.0000003	0.0000005	0.3352847	0	0.1304348	0.4545455	0.9202650	0.361	6.382

By using the data pertaining to the initial condition, best ten conditions and the optimal condition of the quality characteristics, normalized quality costs (C_{ij}) were calculated and the results are presented in Table 3.17.

The improvements achieved are calculated by including the normalized costs (C_{ij}) as shown below.

- *Best 10 conditions and the initial condition* = $-2.358 - (-6.021) = 3.663 \text{ dB}$
- *The optimal and the initial condition* = $0.361 - (-6.021) = 6.382 \text{ dB}$

Quality costs (L_{ij}) without normalization were calculated by using the data pertaining to the initial condition, best ten conditions and the optimum condition of each quality characteristic and the results are given in Table 3.18.

Table 3.18 S/N ratios according to the non-normalized costs

		Starting Condition	Best 10 Condition	Optimum Condition	Improvement compare with starting condition and best 10 (dB)	Improvement compare with starting condition and optimum condition (dB)
Flexibility	S/N	37.26	40.14	42.01	2.88	4.75
	L _{1j}	0.0001879	0.0000969	0.0000630		
View	S/N	14.95	#SAYI!	#SAYI!	#SAYI!	#SAYI!
	L _{2j}	0.0320073	0.0000000	0.0000000		
Weight	S/N	56.38	59.59	65.23	3.21	8.85
	L _{3j}	0.0000023	0.0000011	0.0000003		
Hardness	S/N	59.59	60.97	63.01	1.38	3.42
	L _{4j}	0.0000011	0.0000008	0.0000005		

Since the L_{ij} value is zero for the view response variable in 10 best combinations and the optimum level, S/N ratio value cannot be calculated. The reason for this condition is that the process is running smoothly and no nonconformities regarding the appearance is present. In order to demonstrate the achieved improvement rate, a

“dummy” number was used. For the ten best conditions if L_{ij} is 0.00001, S/N value is calculated as 50 dB, and for the optimum condition if L_{ij} is 0.00001 S/N value is calculated as 50 dB.

According to the non-normalized costs (L_{ij}), achieved improvement that is not taken into consideration are as follows.

➤ Flexibility

○ *Best 10 values and initial condition* = $40.14 - 37.26 = 2.88 \text{ dB}$

Optimal and initial condition = $42.01 - 37.26 = 4.75 \text{ dB}$

➤ View

○ *Best 10 values and initial condition* = $50 - 14.95 = 35.05 \text{ dB}$

Optimal and initial condition = $50 - 14.95 = 35.05 \text{ dB}$

➤ Weight

○ *Best 10 values and initial condition* = $59.59 - 56.38 = 3.21 \text{ dB}$

Optimal and initial condition = $65.23 - 56.38 = 8.85 \text{ dB}$

➤ Hardness

○ *Best 10 values and initial condition* = $60.97 - 59.59 = 1.38 \text{ dB}$

Optimal and initial condition = $63.01 - 59.59 = 3.42 \text{ dB}$

When examining the verification results, it is seen that significant improvements in flexibility, weight and hardness quality characteristics were achieved. In spite of the good results obtained for the view quality characteristic and the good conditions in which all parts leave the production line, no improvement result in dB units could be delivered. In order to demonstrate the improvement a “dummy” value was used, and the results were suitable to be presented in dB units.

As a result of the confirmation experiment, the suitability of the optimum combination $A_3B_2C_1D_2E_1F_2$ obtained through Taguchi experiment design was confirmed. Response variables flexibility, view, weight, and hardness values were drawn closer to the nominal level. It was seen that especially the quality characteristic that triggered the customer complaint flexibility approached the nominal value quite significantly.

3.5.5 Control Phase

As point out Hsieh et al. (2007), what the aim of this control phase is not only applying already accepted solutions but also guaranteeing implementing continuous improvement at all time. It is the phase, in which the required control and monitoring operations are performed for the process to continue under the improved conditions. As shown in Figure 3.16, Six Sigma team performed before-after analysis in order to standardize the process and to control the process capability.

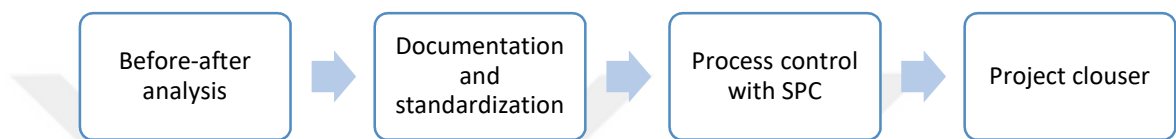


Figure 3.16 Control phase

Optimum factor levels and the values of these levels verified following the improvement phase are shown in Table 3.19.

Table 3.19 Before-After comparison

Factor Knowledge			Before	After
Code	Control factor	Unit	(A ₂ B ₂ C ₁ D ₂ E ₁ F ₁)	(A ₃ B ₂ C ₁ D ₂ E ₁ F ₂)
A	Cooling time	Sec.	10	15
B	Injection pressure	Bar	450	450
C	Injection speed	cm/s	5	5
D	Melt Temperature	°C	480	480
E	Mold Temperature	°C	150	150
F	Wall Thickness	mm	2.10	2.15

As shown in Table 3.19, the cooling time went up from 10 seconds to 15 seconds and the wall thickness of the seal from 2.10 mm up to 2.15 mm.

Optimum factor levels, namely the combination $A_3B_2C_1D_2E_1F_2$ obtained with the Taguchi experiment design were standardized and documented in order to secure the continuity of the improvements achieved. The part number of the door glass seal was revised as MTA2034X. ABC car manufacturer wants to reduce the customer

complaints concerning the front door glass seals to a minimum. Therefore, the contract was renewed in consultation with the rubber manufacturer to include the revised specification value for the glass seal flexibility as 9 ± 0.5 Newton.

A process capability analysis was conducted by using the new specification limits. Relevant data were collected by five samples from each shift, in a 10-day long period. 150 measurements in total were performed. These measurement results are shown in Table 3.20.

Table 3.20 Data after improvement

Shift	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10
S1	9.07	9.11	9.16	8.88	9.10	8.88	9.03	9.07	9.35	9.11
S1	9.10	9.40	8.96	9.24	8.97	9.02	9.25	9.12	9.06	9.13
S1	9.15	9.23	8.88	9.06	8.99	9.23	8.93	9.22	9.12	9.02
S1	9.19	8.89	9.18	9.05	9.06	9.22	8.89	8.89	9.10	8.91
S1	9.25	8.98	9.28	9.24	9.16	8.97	8.91	9.13	9.08	9.10
Average of S1	9.15	9.12	9.09	9.09	9.06	9.06	9.00	9.09	9.14	9.05
Range of S1	0.18	0.51	0.40	0.19	0.35	0.35	0.36	0.33	0.29	0.22
S2	9.16	9.04	8.97	9.27	9.07	9.20	9.20	9.18	9.01	8.98
S2	9.08	9.26	9.09	8.95	8.98	8.96	9.16	9.05	9.01	8.98
S2	9.35	9.19	9.09	9.07	9.01	9.00	9.26	9.30	9.34	8.99
S2	9.29	9.23	9.11	9.32	9.18	8.96	9.21	9.03	9.25	9.19
S2	9.16	9.08	9.13	8.92	9.17	9.28	9.18	9.12	9.25	9.15
Average of S2	9.21	9.16	9.08	9.11	9.08	9.08	9.20	9.14	9.17	9.06
Range of S2	0.27	0.22	0.16	0.40	0.20	0.32	0.10	0.27	0.33	0.21
S3	8.88	9.09	8.75	9.16	8.92	9.07	9.11	9.15	9.18	9.01
S3	9.13	9.00	9.19	9.31	9.07	8.94	8.81	8.97	9.13	8.89
S3	9.17	9.17	8.97	9.26	8.94	9.10	9.08	8.93	8.96	9.17
S3	9.01	9.10	8.92	9.06	9.07	9.08	9.04	9.20	9.23	9.07
S3	8.91	9.05	9.13	9.08	9.07	9.07	9.22	9.07	9.12	9.05
Average of S3	9.02	9.08	8.99	9.17	9.01	9.05	9.05	9.06	9.12	9.04
Range of S3	0.29	0.17	0.44	0.25	0.15	0.16	0.41	0.27	0.27	0.28

A normality test on the measurement results was performed to check the normal distribution of the data. As shown in Figure 3.17, $P - Value = 0.547$ and $A^2 = 0.31$ results indicate the normal distribution of data.

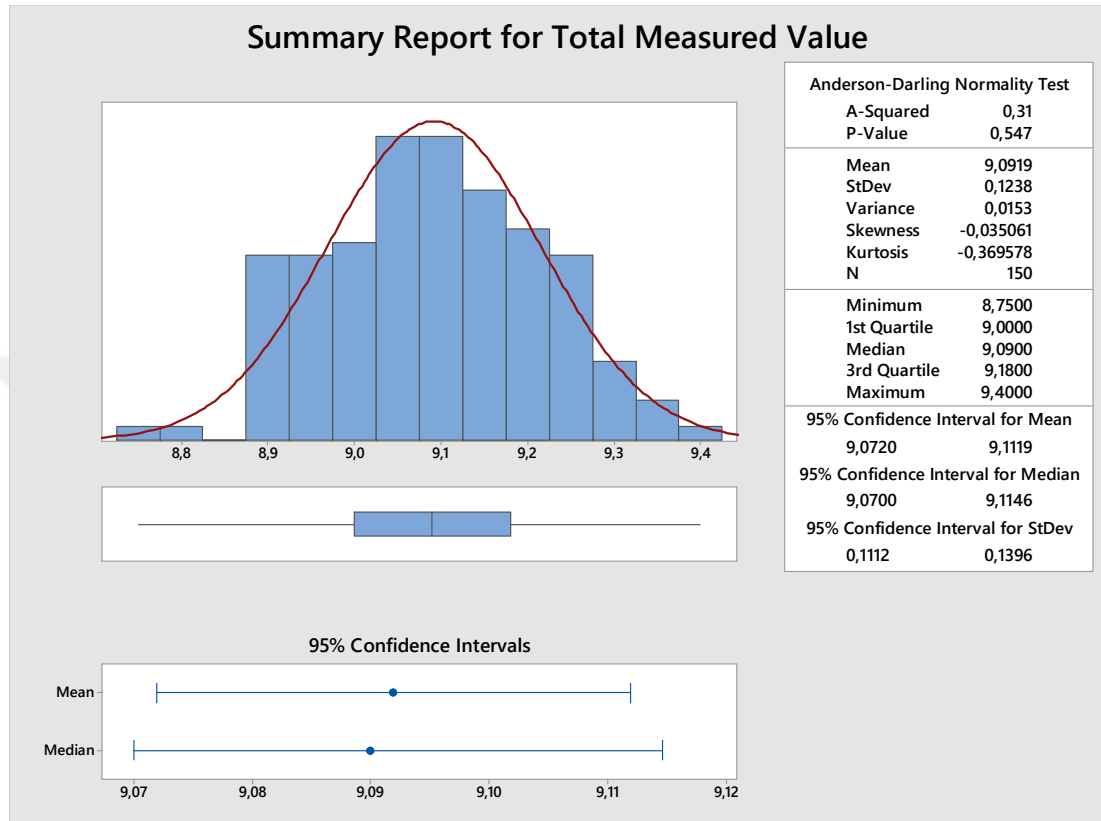


Figure 3.17 Normality test for improved result

Following the normal data distribution, an $\bar{X} - R$ control chart was drawn up to check for the stability of the process and whether the production is in control. When the $\bar{X} - R$ control chart result was examined, no special cause was observed, and it was seen that the observations were in the vicinity of average values. Under these circumstances, it can be deduced that the process is stable.

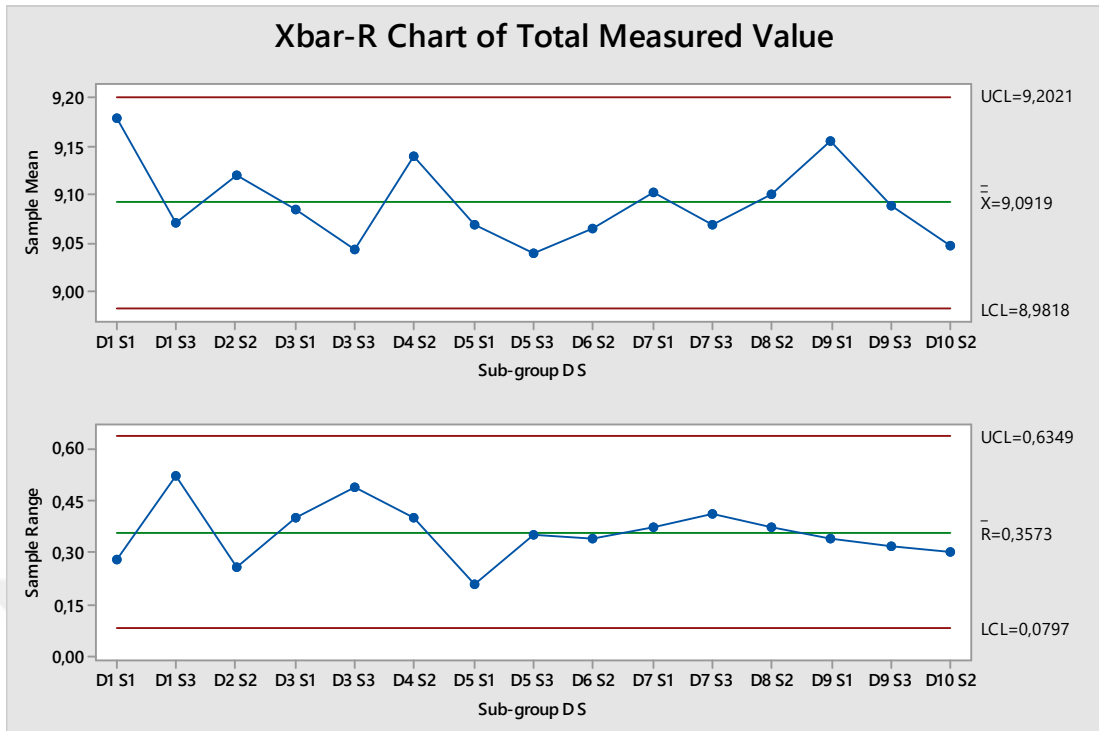


Figure 3.18 $\bar{X} - R$ chart

Process capability analysis was performed in order to evaluate the capability of the process and shown in Figure 3.19.

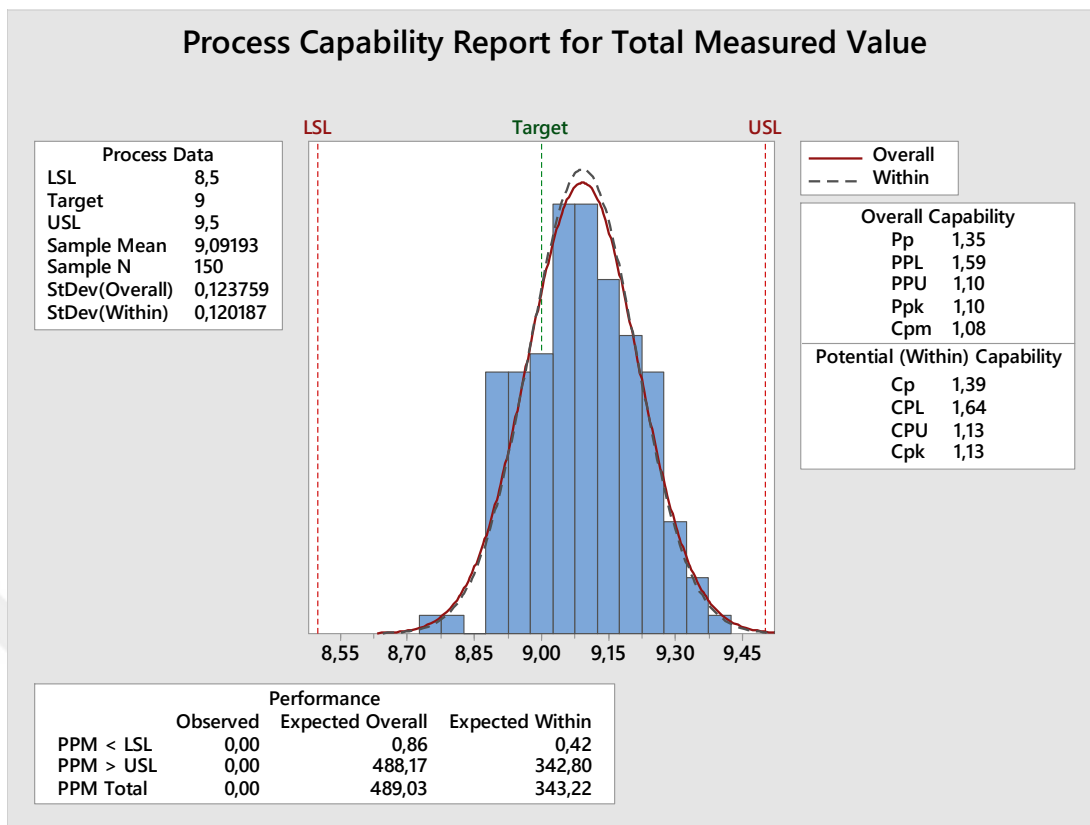


Figure 3.19 Process capability index

Since the target value (\bar{x}) does not coincide with the process mean in the process capability analysis, C_{pk} value was taken into consideration. The calculation delivers the following outcome: $C_{pk} = 1.13$. This value proves the improvement in the process capability, consequent upon the Six Sigma project. The process average was brought reasonably close to the nominal value with 9.09193 Newton. The process capability rate is calculated as shown below:

$$PCR = \frac{1}{C_p} = \frac{1}{1.39} = 0.719 \quad (3.52)$$

The obtained PCR value shows that 71.9% of the production line is in use.

$$UNTL = \bar{x} + 3\hat{\sigma} = 9.0919 + 3 \times 0.123759 = 9.463177 \quad (3.53)$$

$$LNTL = \bar{x} - 3\hat{\sigma} = 9.0919 - 3 \times 0.123759 = 8.720623 \quad (3.54)$$

$$UCL_{\bar{X}} = \bar{\bar{X}} + A_2\bar{R} = 9.0919 + 0.577 \times 0.3573 = 9.2980621 \quad (3.55)$$

$$LCL_{\bar{X}} = \bar{\bar{X}} - A_2\bar{R} = 9.0919 - 0.577 \times 0.3573 = 8.8857379 \quad (3.56)$$

In Figure 3.20 it can be seen that the NTL and CL limits are within contract limits, which is the desired condition.

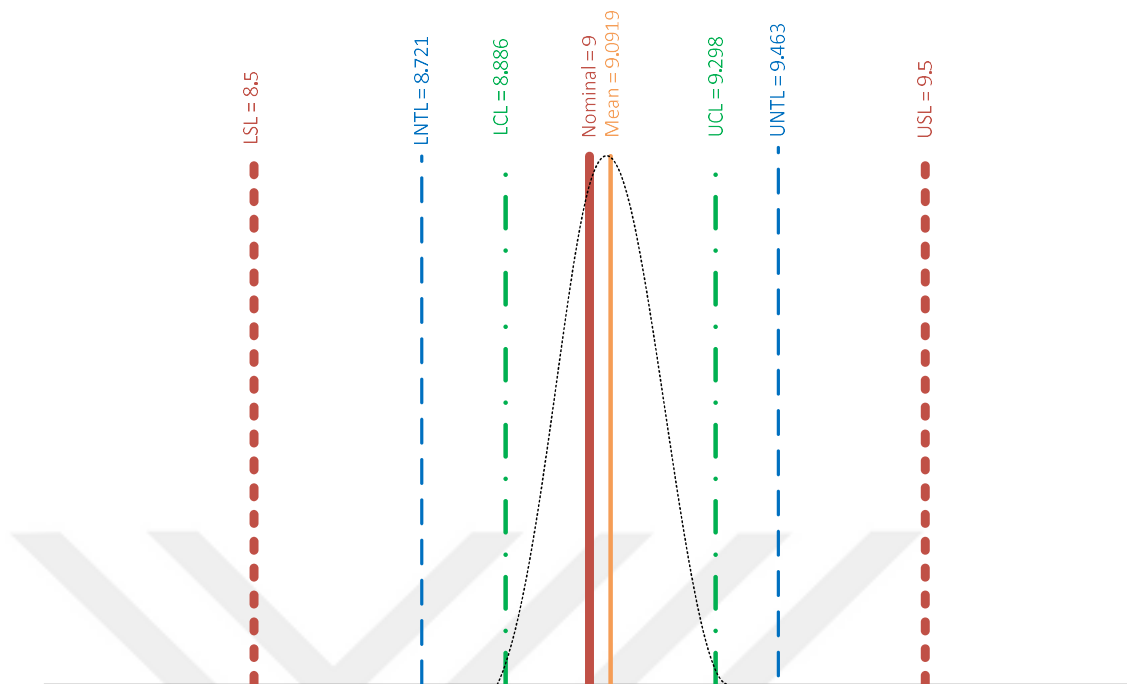


Figure 3.20 Comparison of natural tolerance limits with specification and control limits

As shown in Figure 3.20 the process was significantly improved following the Six Sigma project. Statistical improvement results obtained through the Six Sigma project conducted to eliminate the flexibility problem of the door glass seal are given below.

- Process mean increased from 7.0951 Newton to 9.0919 Newton.
- The sigma level of the process increased from 2.21σ to 4.80σ .
- The standard deviation of the process decreased from 0.140589 to 0.123759.

Process capability was ensured as a result of the Six Sigma project. Six Sigma team have taken following actions to ensure that the process capability stays permanently within customer specification limits:

- The personnel deployed in the process will attend annual refreshment trainings regularly covering the following steps: placement of the door glass seal into the measurement device, performing the measurement and recording of the measurement results.
- It was ensured that the basic maintenance for the measurement device was performed and recorded on a daily basis. The calibration periods are monitored digitally through a newly acquired maintenance software. The maintenance

records of the equipment used in the process are regularly shared with the personnel tasked with performing the process.

- The personnel are planned to regularly go through awareness tests and eye examinations.
- The project quality engineer initiated regular measurement system analyses (Gage R&R) on a weekly basis. The results are monitored with live feed and urgent actions are taken if necessary. The management is informed in the first production assessment meeting of the week.
- The decision was made to generalize the Six Sigma projects within the company. In the initial stage, two production and three quality engineers are to attend Six Sigma training.

The rubber seals coming off the machine are cooled down in a cooling bath. As a result of the Taguchi experiment design, the cooling time was increased from 10 seconds to 15 seconds. Hence the rubber profiles stay for a longer period in the cooling bath, and the amount of door glass seal produced in a single shift decreased from 350 to 320. The comparison of annual production results before and after the project is shown in Figure 3.21.

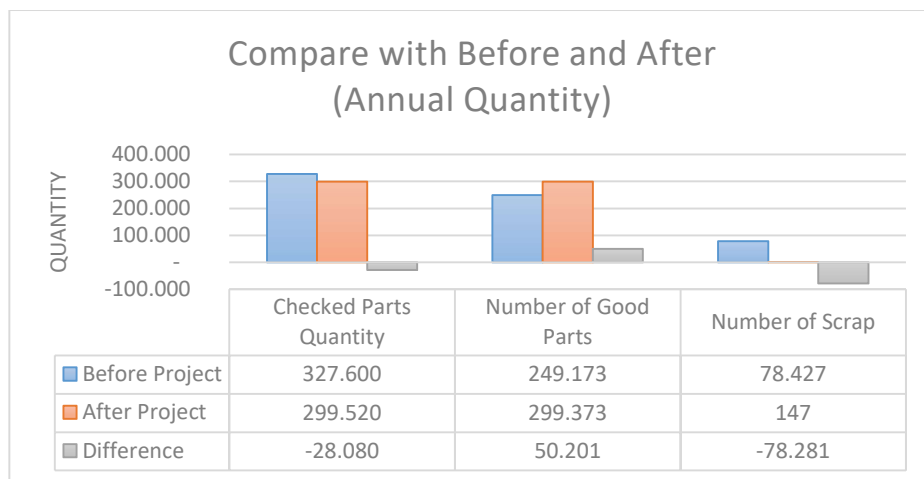


Figure 3.21 Comparison of before and after quantities

As can be seen in Figure 3.21 the annual production quantity decreased by 28,080. The scrap amount decreased from 78,427 to just 147 along with the scrap rate going

down from 23.940% to 0.049%. Therefore, a number of conforming products experienced an annual step-up of 50,201.

In accordance with the contract, a single front door glass seal is sold to ABC car manufacturer for approximately \$6. Gross profit and loss comparison of before-project and after-project are shown in Figure 3.22. The scrap cost decreased by \$469,684 and the conforming product revenue increased by \$301,204. Through the project, a \$770,888 gross profit increase was achieved.

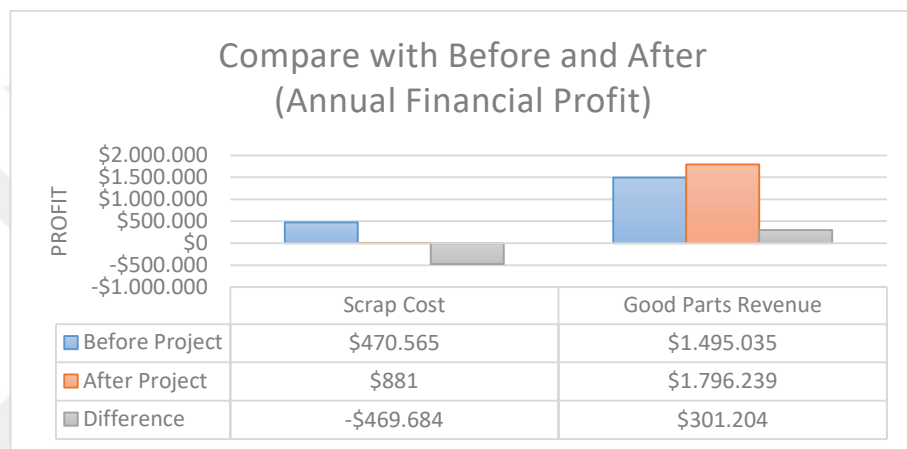


Figure 3.22 Comparison of before and after profit

In addition, an increase in the amount of used dough was occurred by raising the glass seal wall thickness from 2.10 mm up to 2.15 mm following the project.

Table 3.21 Comparison of before-project and after-project

Comparison of before-project and after-project	Weight (Gr.)
Before Project	320.331
After Project	320.956
Difference	0.625

As shown in Table 21, with the increasing wall thickness the amount of dough to be used for a single door glass seal went up from 320.331gr to 320.956 gr, an increase of 0.625 gr per product. It is known that the 1000 gr of door glass seal dough cost \$5.2. In this case, the cost of the extra 0.625 gr dough is $3.25 * 10^{-3}$ USD. An annual cost increase of \$973 ($3.25 * 10^{-3} \$ * 299,520 \text{ qty./year}$) was the result of the project. The project gross profit was calculated as follows by taking the increasing dough cost into consideration:

$$\text{Project Gross Profit} = \text{Profit} - \text{Costs} = \$770,888 - \$973 = \$769,915 \quad (3.57)$$

The results acquired in the control phase show that the glass seal flexibility value is drawn near to the nominal value. Six Sigma team arranged a closing meeting following the successful execution of the project. A presentation was prepared in order to outline the improvement to the management achieved with the project. The success of the project was approved by the management.

CHAPTER FOUR

CONCLUSION

In today's global economy, the especially automotive industry which is the leading industry, face fierce competition. Indeed, the competitive pressure is steadily growing. To remain competitive, manufacturer companies must be therefore continuously efficient and improve. For this reason, companies are producing their products or service in order to satisfy their customers. In order to do this, companies are using highly statistical tools and technics. These tools and technics play the important role to identify and control the processes during production. There are several managing and scientific ways to use these technics. These managerial approaches are usually the resultant methodologies of the evolution of previous approaches.

One of these new management approaches that align organizational strategy, performance improvements, and customer satisfaction was presented and evaluated in a real environment. This management approach, named Six Sigma closed the gap between strategy's design and strategy's implementation and between improvement initiatives, and organizational output. As known that Six Sigma in all around the world is quite effective. Six Sigma can be created with the right corporate infrastructure in all of the sectors.

Six Sigma tools that were applied in the case study were effective in helping to identify and eliminate wasteful activities. Measurement system analysis, statistical process control, the design of experiment techniques, etc., helped to collect detailed information that was critical to understand the processes and identify the gaps compared to best practice. Having process analysts with experience in implementing Six Sigma tools, knowledge of financial processes and information systems was important to identifying improvements that eliminated root causes and waste.

The very power of Six Sigma is in its breadth of application of data tools and techniques. Therefore, before initiating any Six Sigma project the team needs to attend an extensive training, comprising statistical methods to be used in DMAIC problem-

solving steps. Since statistics make up the backbone of Six Sigma, the correct use of statistical means and techniques in projects are of utmost importance.

One of the reasons behind the selection of the rubber manufacturing company for the application is the willingness to cooperate and ascribing importance to the university-industry collaboration. As a result of this collaboration, it was ensured that the statistical techniques used within the scope of DMAIC problem-solving methodology were employed in a timely and appropriate manner.

This case study research allowed the design, implementation, and evaluation of the Six Sigma approach in the natural organizational environment. It plays the important role to make Six Sigma successful because the problem focused on not only based on customer's need but also based on the production process of the front door window. First of all, the problem has been identified and then measurement system has been verified. In order to verify the system, process productivity analysis has been performed and the caused problem has been identified. Continuous improvement has been performed by eliminating factors caused by process insufficiency and by eliminating effects. For this, improvement phase of Six Sigma methodologies has been used Multi Response Taguchi Design of Experiment (MRSN). As is well known, the Taguchi experimental design employed in the improvement phase of many Six Sigma projects might neglect other quality characteristics, while focusing on a single one. This circumstance may have a negative influence on the financial state of the company, product/service quality, and customer satisfaction. In this study; the possibility of an adjustment made on the cooling time, injection pressure, injection speed, melt temperature, mold temperature and wall thickness factors and levels to affect the flexibility of the front door glass seal along with the appearance, weight and hardness quality characteristics was evaluated by applying the "multi response signal noise" Taguchi experiment design. Consequently, it was ensured that the remaining quality characteristics of importance to the customer were taken equally into consideration. Therefore, continuous improvement is satisfied not only by having response variable but also by identifying a quality characteristics of the product. By using MRSN Taguchi design of experiment, continuous improvement of quality characteristics has

been identified not only on the flexibility of front door window value but also on view, weight, and hardness. As shown in Table 4.1 the comparison is made between the initial condition and the optimal condition for all quality characteristics.

Table 4.1 Comparison of confirmation data with the initial condition and the optimal condition

Response Variables	Statistics	Initial Condition (A₂B₂C₁D₂E₁F₁)	Optimal Condition (A₃B₂C₁D₂E₁F₂)
Flexibility	Average	8.768	9.045
	Std.Dev.	1.322	0.072
	Variance	1.748	0.005
	Range	3.760	0.240
Appearance	Average	0.981	1.000
	Std.Dev.	0.135	0.000
	Variance	0.018	0.000
	Range	1.000	0.000
Weight	Average	320.331	320.956
	Std.Dev.	3.673	0.185
	Variance	13.492	0.034
	Range	11.900	1.060
Hardness	Average	67.171	67.508
	Std.Dev.	0.735	0.046
	Variance	0.540	0.002
	Range	2.370	0.180

The nominal value of flexibility, weight, appearance, and hardness is 9 Newton, 1,321 gr, and 67.5 shores, respectively. The improvement results of the quality characteristics achieved following the multi response Taguchi experiment design are statistically compared with the values before the project. Statistical comparisons for each quality characteristic is given below:

- Flexibility: Flexibility value drew considerably near to the nominal value with an increase from 8.768 Newton up to 9.045 Newton. The variance of the flexibility decreased from 1.748 Newton down to 0.005 Newton, and the range declined from 3.760 Newton back to 0.240 Newton. These statistics prove the

improvement of the flexibility quality characteristic which originally triggered the customer complaint.

- Appearance: For this quality characteristic, “1” was set to a threshold value verifying that the product is conforming. The average value of appearance, which was 0.981 before the project, was brought up to the target value “1” as a result. The variance was reduced from 0.018 down to 0, and the range value was improved by a decrease down 1 to 0. The variance and range values being at 0 verifies the improvement achieved in the appearance.
- Weight: The weight of the front door glass seal approached 321 gr, which is the nominal value. The variance was minimized by pulling the variance value from 13.492 down to 0.034. In a similar manner, the range value went from 11.900 down to 1.060. These values verify the improvement accomplished for this quality characteristic.
- Hardness: The average of the hardness quality characteristic was brought from 67.171 Shore an up to 67.508 Shore A, and the nominal value was achieved. The variation of the hardness was lowered from 0.540 down to 0.002 along with the range value decreasing from 2.370 to 0.180. These statistical values verify that the hardness of the front door glass seal reached the nominal value.

In order to avoid any customer complaints with the front door window, the statistical values/results from Taguchi test help to prove the success of this project.

To be successful in Six Sigma projects, having and using a statistical technic will be helpful not only in automotive industry but also aerospace, defense, chemistry health, service, R&D and public industries. For this reason, employees, who would have a statistical background, will be beneficial for Six Sigma projects.

As we all know, Six Sigma concept was born in real industry and spread through universities. There are many universities, collaborating and working with different companies successfully. The best example is Motorola and how Six Sigma was born in this facility, and now it is a degree program at Motorola University. There are

several other universities in the world, which offer Ph.D. degree programs in Six Sigma.

Cyber-physical systems are now active with the introduction of the fourth phase of the industrial age in 2011. The integration of Six Sigma with the innovation has become inevitable in the context of Industry 4.0. The scope of application of Six Sigma is destined to expand much more broadly and rapidly during Industry 4.0, than ever.



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APPENDICES

Table A1. Detailed conversion between ppm (or DPMO) and sigma quality level when the process mean is $\pm 1.5\sigma$ shifted (Park, 2003).

Sigma Level	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
2,00	308.770,2	305.249,8	301.747,6	298.263,7	294.798,6	291.352,3	287.925,1	284.517,3	281.129,1	277.760,7
2,10	274.412,2	271.084,0	267.776,2	264.489,0	261.222,6	257.977,2	254.753,0	251.550,2	248.368,8	245.209,2
2,20	242.071,5	238.955,7	235.862,1	232.790,8	229.742,0	226.715,8	223.712,2	220.731,6	217.773,9	214.839,2
2,30	211.927,7	209.039,6	206.174,8	203.333,5	200.515,7	197.721,6	194.951,2	192.204,6	189.481,9	186.783,0
2,40	184.108,2	181.457,4	178.830,7	176.228,0	173.649,5	171.095,2	168.565,1	166.059,2	163.577,5	161.120,1
2,50	158.686,9	156.278,0	153.893,3	151.532,9	149.196,7	146.884,7	144.596,8	142.333,2	140.093,6	137.878,1
2,60	135.686,7	133.519,3	131.375,8	129.256,3	127.160,5	125.088,6	123.040,3	121.015,7	119.014,7	117.037,0
2,70	115.083,0	113.152,2	111.244,7	109.360,2	107.498,9	105.660,5	103.844,9	102.052,1	100.281,9	98.534,3
2,80	96.809,0	95.106,1	93.425,3	91.766,6	90.129,8	88.514,8	86.921,5	85.349,7	83.799,3	82.270,1
2,90	80.762,1	79.275,0	77.808,8	76.363,2	74.938,2	73.533,6	72.149,1	70.784,8	69.440,4	68.115,7
3,00	66.810,6	65.525,0	64.258,6	63.011,3	61.783,0	60.573,4	59.382,5	58.210,0	57.055,8	55.919,6
3,10	54.801,4	53.700,9	52.618,1	51.552,6	50.504,3	49.473,1	48.458,8	47.461,2	46.480,1	45.515,3
3,20	44.566,8	43.634,2	42.717,4	41.816,3	40.930,6	40.060,2	39.204,9	38.364,5	37.538,9	36.727,8
3,30	35.931,1	35.148,6	34.380,2	33.625,7	32.884,8	32.157,4	31.443,3	30.742,5	30.054,6	29.379,5
3,40	28.717,0	28.067,1	27.429,4	26.803,8	26.190,2	25.588,4	24.988,2	24.419,5	23.852,1	23.295,8
3,50	22.705,4	22.215,9	21.692,0	21.178,5	20.675,4	20.182,4	19.699,5	19.226,4	18.763,0	18.309,1
3,60	17.864,6	17.429,3	17.003,2	16.586,0	16.177,5	15.777,7	15.386,5	15.003,5	14.628,8	14.262,2
3,70	13.903,5	13.552,7	13.209,5	12.873,8	12.545,5	12.224,5	11.910,7	11.603,9	11.303,9	11.010,7
3,80	10.724,2	10.444,1	10.170,5	9.903,1	9.641,9	9.386,7	9.137,5	8.894,1	8.656,4	8.424,2
3,90	8.197,6	7.976,3	7.760,3	7.549,4	7.343,7	7.142,8	6.946,9	6.755,7	6.569,1	6.387,2
4,00	6.209,7	6.036,6	5.867,8	5.703,1	5.542,6	5.386,2	5.233,6	5.084,9	4.940,0	4.798,8
4,10	4.661,2	4.527,1	4.396,5	4.269,3	4.145,3	4.024,6	3.907,0	3.792,6	3.681,1	3.572,6
4,20	3.467,0	3.364,2	3.264,1	3.166,7	3.072,0	2.979,8	2.890,1	2.802,8	2.717,9	2.635,4
4,30	2.555,1	2.477,1	2.401,2	2.327,4	2.255,7	2.186,0	2.118,2	2.052,4	1.988,4	1.926,2
4,40	1.865,8	1.807,1	1.750,2	1.694,8	1.641,1	1.588,9	1.538,2	1.489,0	1.441,2	1.394,9
4,50	1.349,9	1.306,2	1.263,9	1.222,8	1.182,9	1.144,2	1.106,7	1.070,3	1.035,0	1.000,8
4,60	967,6	935,4	904,3	874,0	844,7	816,4	788,8	762,2	736,4	711,4
4,70	687,1	663,7	641,0	619,0	597,6	577,0	557,1	537,7	519,0	500,9
4,80	483,4	466,5	450,1	434,2	418,9	404,1	389,7	375,8	362,4	349,5
4,90	336,9	324,8	313,1	301,8	290,9	280,3	270,1	260,2	250,7	241,5
5,00	232,6	224,1	215,8	207,8	200,1	192,6	185,4	178,5	171,8	165,3
5,10	159,1	153,1	147,3	141,7	136,3	131,1	126,1	121,3	116,6	112,1
5,20	107,8	103,6	99,6	95,7	92,0	88,4	85,0	81,6	78,4	75,3
5,30	72,3	69,5	66,7	64,1	61,5	59,1	56,7	54,4	52,2	50,1
5,40	48,1	46,1	44,3	42,5	40,7	39,1	37,5	35,9	34,5	33,0
5,50	31,7	30,4	29,1	27,9	26,7	25,6	24,5	23,5	22,5	21,6
5,60	20,7	19,8	18,9	18,1	17,4	16,6	15,9	15,2	14,6	13,9
5,70	13,3	12,8	12,2	11,7	11,2	10,7	10,2	9,8	9,3	8,9
5,80	8,5	8,2	7,8	7,5	7,1	6,8	6,5	6,2	5,9	5,7
5,90	5,4	5,2	4,9	4,7	4,5	4,3	4,1	3,9	3,7	3,6
6,00	3,4	3,2	3,1	2,9	2,8	2,7	2,6	2,4	2,3	2,2
6,10	2,1	2,0	1,9	1,8	1,7	1,7	1,6	1,5	1,4	1,4
6,20	1,3	1,2	1,2	1,1	1,1	1,0	1,0	0,9	0,9	0,8
6,30	0,8	0,8	0,7	0,7	0,6	0,6	0,6	0,6	0,5	0,5
6,40	0,5	0,5	0,4	0,4	0,4	0,4	0,4	0,3	0,3	0,3
6,50	0,3	0,3	0,3	0,2	0,2	0,2	0,2	0,2	0,2	0,2
6,60	0,2	0,2	0,2	0,1	0,1	0,1	0,1	0,1	0,1	0,1
6,70	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
6,80	0,1	0,1	0,1	-	-	-	-	-	-	-