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BASKILI DEVRE KARTLARINDA LEHİM BASKI İŞLEMİ ÜZERİNDE DMAIC YAKLAŞIMI

Beyza Nur GİDER (SEZGİN)

YÜKSEK LİSANS TEZİ

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TEZ KABUL VE ONAYI

Beyza Nur GİDER (SEZGİN) tarafından hazırlanan "Baskılı Devre Kartlarında Lehim Baskı İşlemi Üzerinde DMAIC Yaklaşımı" adlı tez çalışması 13/04/2018 tarihinde aşağıdaki jüri tarafından oy birliği ile Necmettin Erbakan Üniversitesi Fen Bilimleri Enstitüsü Endüstri Mühendisliği Anabilim Dalı'nda YÜKSEK LİSANS TEZİ olarak kabul edilmiştir.

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Bu tezdeki bütün bilgilerin etik davranış ve akademik kurallar çerçevesinde elde edildiğini ve tez yazım kurallarına uygun olarak hazırlanan bu çalışmada bana ait olmayan her türlü ifade ve bilginin kaynağına eksiksiz atıf yapıldığını bildiririm.

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Beyza Nur GİDER (SEZGİN)

Tarih: 14.02.2018

ÖZET

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Günümüzde şirketler, rekabet edebilmek için küreselleşmiş pazarda koydukları ürün çeşitliliğini artırmaktadır. Bu çeşitlilik ve rekabet, şirketleri gerekli kalitede verimli bir şekilde üretmeye zorlamaktadır. Hatalı ürünler, imalatçılar için çok önemli bir konudur. İşlemdeki kusurları belirlemek uzun zaman alabilir. Düşük hata seviyelerine sahip tekrarlayan ve olgunlaşmış süreçler, Milyonda hata olasılığı (DPMO) ile ölçülür ve bunları daha da azaltmak zordur. Bu durumlarda, şirketler yüksek kalite, düşük maliyet, etkin süreç ve yüksek müşteri memnuniyeti sağlamak için yeni yöntemler araştırmaktadır.

Bu tezin amacı, tek bir süreçte kusur oranını azaltmaya odaklanmaktır. Özellikle, yüksek kalite seviyesindeki süreçleri ele alarak, daha iyi bir performans sağlamak için Altı Sigma kullanılmaktadır.

Metodoloji, elektrik ve elektronik cihazların üreten bir otomotiv tedarikçisinin uzunlamasına incelemesine dayanmaktadır. Yüzey montaj teknolojisinde (SMT) Baskılı Devre Kartlarının (PCB'ler) lehim pastası baskı sürecini geliştirmek için DMAIC döngüsü kullanılarak Altı Sigma araçları uygulanmıştır.

Bu çalışmada, lehim macununda oluşan hacim kusuru, süreçte oluşan en yaygın kusur türü olarak tanımlanmıştır. Süreçte kullanılan yöntem (proflow) istatistiksel analizler kullanılarak seçilen yeni bir yöntem (squeegee) ile karşılaştırılmıştır.

Baskı işleminde yapılan değişiklikler, hacim kusurunu %50' nin altına düşürmüştür (DPMO, 243'den 118'e indirgendi). Sigma seviyesi 5.0'dan 5.2'ye çıkartılmıştır.

Bu çalışma, DMAIC'in bu alanda yayınlanmış diğer çalışmalarını doğrulayarak, süreç analizi ve iyileştirmesi için yeterli bir metodoloji olduğunu göstermektedir.

Anahtar Kelimeler: Altı Sigma, DMAIC, Yüzey Montaj Teknolojisi- Bakı Süreci

ABSTRACT

MS

DMAIC APPROACH TO SOLDER PRINTING PROCESS IN PRINTED CIRCUIT BOARDS

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Nowadays, companies are increasing the diversity of products they put in the globalized market to become more competitive. This diversity and competition are pushing companies to produce efficiently with the required quality. Production of defective items is a crucial issue for manufacturers. It could take long time to identify defects in the process. In repetitive and mature processes with low defect levels, typically measured by defects per million opportunities (DPMO), is difficult to reduce them even further. In these cases, companies are looking for new methodologies to achieve high quality, low cost, effective process and high customer satisfaction.

The purpose of this thesis is to focus on the reducing of defects rate in one key process. Particularly, it will address processes with high quality level and will use Six Sigma to provide a better performance.

The methodology is based on a longitudinal case study of an automotive supplier of electrical and electronic devices. It focuses on implementing Six Sigma tools, using the DMAIC cycle to improve the solder paste printing process of Printed Circuit Boards (PCBs) in surface mount technology (SMT).

In the case study, solder paste volume defect is defined as the most common type of defect occurred in the process. The used method (proflow) was compared with a new selected method (squeegee) using statistical analyses.

The changes carried out in the printing process were successful since the volume defect was reduced over 50% (DPMO reduced from 243 to 118) and, consequently, the sigma level was increased from 5.0 to 5.2.

This study shows that DMAIC is an adequate methodology for process analysis and improvement, corroborating, thus, other studies published in this domain.

Keywords: Six Sigma, DMAIC, Surface Mount Technology – Printing Process

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ABBREVIATIONS

3D -	Three Dimension
5S -	*Seiri, Seiton, Seiso, Seiketsu, Shitsuke*
7M -	Affinity Diagrams, Tree Diagrams, Interrelationship Diagraph, Process Decision, Program Charts, Matrix Diagrams, Prioritization Matrices, Activity Network diagram
AHP -	Analytic Hierarchy Process
AOI -	Optical Inspection Equipment
CI -	Consistency Index
CR -	Consistency Ratio
DMADV -	Define, Measure, Analyse, Design, Verify
DMAIC -	Define, Measure, Analyse, Improve, Control
DPMO -	Defects per Million Opportunities
DPU -	Defects per Unit
FMEA -	Failure Modes and Effects Analysis
IAP -	In case of non-conformities at the checkpoint
PCB -	Printed Circuit Board
PPM -	Parts per Million
RI -	Random Index
QFD -	Quality Function Deployment
SIPOC -	Supply, Input, Process, Output, Customer
SMC -	Scrum Master Certified
SMD -	Surface Mount Devices
SMT -	Surface Mount Technology
SPC -	Statistical Process Control
VOC -	Voice of Customer
VW -	Volkswagen

1. INTRODUCTION

On this chapter introduction related to the field of study, the main objective as well as the background of this study is presented. At the end of the chapter, the document structure is summarized.

1.1. Background

Vehicle electronic companies that supply sensors, powertrain, monitor, and panel for hard disk drive "carputers" telematics, in-car entertainment systems are striving to produce the most remarkable devices in the global competition. Big enterprises which have had high profit margins are facing a number of challenges that threaten to change and develop this industry. In this industry, the innovative products and the development of new products and production systems are important to assure competitiveness.

The automotive electronic suppliers in this area have successfully implemented quality managements systems and quality tools and techniques to support these systems. The prerequisites for the improvement of manufacturing processes in the electronics field are the continuous growth of different technologies; as well as the increased quality requirements of quality control and output products. The environment associated with surface mount technology manufacturing, has been successfully compatible with Six Sigma methodology, unlike other sectors where quality management concept has been implemented and exploited.

Six Sigma is a methodology of carried out a project to reduce process variability and defects by using the methodology DMAIC (acronym for five phases that make up the improvement cycle – Define, Measure, Analyse, Improve and Control. This methodology was used in Printed Circuit Board (PCB) manufacturing, particularly in the solder paste printing process where product failures reduction and continuous improvement are key objectives and are the focus of this work.

This work was developed in Delphi Automotive-Braga, which is an assembly-manufacturing site based in the United States that belongs to Delphi Automotive PLC. Delphi Automotive-Braga manufactures PCB products mostly by using Surface Mount Technology (SMT) which is a technique of placing surface mount devices (SMDs) on the surface of a PCB (Tong, Tsung et al., 2004).

According to Tsai (2008), SMT is an important method used in electronic assembly industry to produce modern electronic products. There are many studies about PCB in different activity sector (Lee, Wei et al., 2009; Winiarz, Fang et al., 2001; Kuptasthien and Boonsompong, 2011; Mozar and Voorthuysen, 2012; Rajewski, 1995). In general, according to Caleb Li, Al-Refaie et al. (2008), SMT production line consists of three manufacturing processes: (1) solder paste printing process; (2) pick-and-place for SMT components (SMC) and (3) reflow of solder paste.

Delphi Automotive-Braga has a wide range of products from simpler to more complexes, and with different customer’s requirements. One of the main challenges that Delphi Automotive-Braga faces is maintaining quality standards in its all products. The main concern for process engineers is improving this process (Caleb Li, Al-Refaie et al., 2008). Therefore, reducing the defect rate in this particular process is the first objective of top management proposed and addressed in this study.

Furthermore, the reduction of defect rates obviously affect the process yield in SMT. Based on this, it becomes important to reduce rejection rates along the printing process in order to obtain high level of performance. The focus of this work is to use the DMAIC methodology in the printing process.

This objective is to use and implement Six Sigma. Particularly, the DMAIC methodology (for process improvement) is used to improve the solder paste printing processes of PCB products and thus reducing the rejection rates associated with this process. By focus on process improvement, the main objectives of this work are:

- Present and understand all details of each step of the solder paste printing process;
- Identify the main type of defects;
- Identify each defect and respective root causes;
- Eliminate the root causes from the processes by developing and implementing new solutions;
- Control the impact of the changes performed

In order to achieve this work’s objectives, a DMAIC methodology (data-driven quality strategy used to improve processes) is going to be applied, and with help of various techniques, each phase of DMAIC will be carried out.

1.2. Document Structure

This document is organized in five different chapters. On the second chapter Six Sigma and its DMAIC methodology are presented in detail besides examples of techniques and tools.

In chapter three, it is characterized the company where this study was applied. It also describes in detail the assembly manufacturing process and the main process focused on.

The fourth chapter is organized according to DMAIC cycle – Define, Measure, Analyse, Improve and Control. In this chapter, types of defect are described and the root cause is designated. Previous method and the new method are compared by calculating sigma levels. The comparison indicates improvement of process.

Finally, on chapter five, it is summarized the achievements of pre-defined objectives and potential future work is proposed.

2. LITERATURE REVIEW

For many years, production has been led a hard working within the automotive industry. This industry is separated into various sub-industries according to their product types, production methods. Since the vehicle production is a complex process, producers need to supply their requirements from different industries such as power-train and chassis, interior parts, body and main parts, electrical and electronics. In order to produce these automotive parts, assembly lines which are common methods of assembling complex items are used in manufactory. Besides the manufacturing, there are many companies which were established for assembling in the industry.

Assembly systems are significant process on global market. In PCB production industry, the most important system is the assembly line and subsequent to printing process – the board printed with solder paste, placing – the components placed on the board, reflow process – soldering flux to match the component by reflow oven. This importance has been reflected by the numbers of published studies, particularly improvement of printing process (Srinivasan, Muthu et al., 2014; Huang, 2010; Caleb Li, Al-Refaie et al., 2008).

PCB device manufactures are looking to Six Sigma principles as the way for significant improvement of operation efficiency and quality, while eliminating defects. Today, managers and engineers are focused as never before on reducing operational costs with those principles. This chapter introduces Six Sigma and DMAIC methodology, its main tools, principles and benefits.

2.1. Six Sigma Definition and Its Origin

The main purpose of companies is to get a profit and only profitable companies can continue their activities. Profit mainly depends on the customers demand for products from the company, but this is just the beginning part. The customer has an expectation of the product or service. Effective work is done by meeting these expectations. Otherwise the companies can’t achieve customer satisfaction. Companies have looked for new approaches to improve operational performance, profitability and competitiveness for long time. Quality management system is a way to provide high performance.

There is a methodology as a quality ideology in industries and its origin is not set of new or unknown, it is named Six Sigma. Pande et al. (2000) believes that Six Sigma was initially found by W. Edwards Deming and Joseph Juran and they have played an effective role in terms of quality.

According to Eckes (2003), many companies have been interesting the Six Sigma methodology for nineteen years. In this case, there is an evaluation in Six Sigma. Linderman, Schroeder et al. (2003) proves that Six Sigma was originated by Motorola Inc. in the USA in about 1985. Motorola was gradually decreasing its success in the market (Larson, 2003). At the same time, Japanese companies dramatically started to enhance its improvement of the quality in the electronic industry and they were taking over the losses that they lost in the market (Linderman, Schroeder et al. 2003). Contrary to this situation, Motorola's business was not based on customer satisfaction. According to Larson (2003), response times were very long and weren't designed for customer satisfaction in Motorola production. On the other hand, Motorola's products were not as good and reliable as they should be. Many defective parts were sent to customers.

For this reason, according to Larson (2003), a group of Motorola managers were sent to Japan to do a comparison on Japanese operation methods and product quality levels. They noticed that the general program of the Japanese focuses on improving operations to provide more service to customers and incorporating every employee into it. The Japanese did not only use their employees physically, they also used their knowledge.

According to Chow (2017), Six Sigma has changed Motorola history by providing benefit based on short manufacturing time and low defectiveness. It shows to the enterprises how to measure and manage the all process in the industries. In this way, it is a flexible methodology aimed reducing defects that can be used in different problems and industries. Larson (2003) has published that Motorola Ceo, Bob Galvin laid down this strategy by traveling all factories in the world. Over times, Six Sigma has turned into a major working style. Thomsett (2004) has shown that The General Electric Company implemented the Six Sigma organization in its entirety in 1995. Six Sigma is both a statistical measure of variation in a process and a strategy of business management, developed by Motorola, to increase quality, eliminate the root causes of defects and reduce variation and defects within its manufacturing processes (Idrissi, Aftais et al., 2017).

After this evaluation, Six Sigma has become a major methodology for quality management system and authorities has defined and applied Six Sigma in many fields.

In this case, Eckes (2003) believes that Six Sigma was implemented to get a profit in the business competition effectively. Thus, according to Parast (2011), Six Sigma is a quality management system that is structured in a never-ending cycle of improvement has drawn attention. Eckes (2003) also believes that Six Sigma is recommended to develop a satisfaction in the current process.

Many of the well-known companies all over the world doing business in sectors strive to have benefit enormously by adopting Six Sigma business approach. Youssouf, Rachid et al. (2014) believe that Six Sigma is a method that bases on a controlled organization for project management. Six Sigma is also a method of improving the quality and profitability based on statistical process control. Statistical analysis and its ideology are methods commonly used by Six Sigma. According to Markarian (2004), Six Sigma is statistically defined a process in which the range between the mean of a process quality measurement and the nearest specification limit is at least six times the standard deviation of the process.

Adams et al. (2003) believe that when choosing the Six Sigma target, it provides world-class job performance appraisal based on statistical value. The real statistical analysis of world processes is mostly related to customer expectations. Adams et al. (2003) also have showed that six sigma provides the sustained solutions in the projects as a technique. The beginning of the Six Sigma methodology is particularly the examination of the problem in every aspect. According to Raghunath and Jayathirtha (2014), Six Sigma detects and eliminates the root problem in the organizations.

Six Sigma is basically a systematic approach that tries to increase efficiency and productivity at the same time. Additionally, Six Sigma focused on defect elimination and basic variability reduction. Various industries applied the Six Sigma for defect or problem reduction and sigma level improvement purposes; for example, in automotive industry, Pugna, Negrea et al (2016) have showed that DPMO were reduced from 81,000 to 108 (improving the riveting process led to 40% defect reduction and choosing the most suitable supplier led to 30% defect reduction). Erbiyik and Saru (2015) have focused on finding causes of the defects, additionally, classified, reduced and sequenced in order of priority by using Six Sigma.

In plastic and a metallurgical industry, Chinbat and Takakuwa (2008) have proved that process bottlenecks were reduced by an approximate average of 72 percent. In construction industry, Han et al. (2008) have showed that the adjusted sigma levels were improved from 4 to 4.5, in an iron bar assembling process. In printed circuit cable assembly line, Kuptasthien and Boonsompong (2011) have showed that the major tombstone capacitor defective rate reduced from 1,154 DPPM to 314 DPPM and increased yield output from 98.4% to 99.66%.

There are many studies that use Six Sigma approaches in service industries such as hospital, Özveri and Dinçel (2012) have increased the sigma level from 2.77 to 4.55 by increasing capacity of physical therapy and rehabilitation policlinic following Six Sigma.

Six Sigma projects can be evaluated by the sigma level. This sigma level is a metric which represents the amount of the variable that is inside specification limits. According to Youssouf, Rachid et al. (2014) the sigma as a Greek letter σ (sigma) that presents the statistical variability, also called standard deviation to measure the dispersion of products around the mean. Six Sigma represents the idealized goal of a defect rate of 3.4 DPMO (defects per million opportunities), or according to Thomsett (2004), 3.4 defective products on a sample of 1 million, which corresponds to a quality rate of 99.9997%. Montgomery (2009) represents that if the customer dissatisfaction is measured as a defect, then Six Sigma indicates that there would be only 3.4 defects for every million opportunities, or near perfection. Adams et al. (2003) believe that the reason of choosing six sigma level is that the five sigma could not meet the customer satisfaction and the seven do not add significant value, as 3.4 DPMO is close the perfection, and that makes it a more attainable and realistic goal to achieve.

Park (2003) shows that specification limits associated to products are performance ranges that customers accept. The specification limits are typically represented by: lower specification limit (LSL), upper specification limit (USL) and target value (T) (Figure 1).

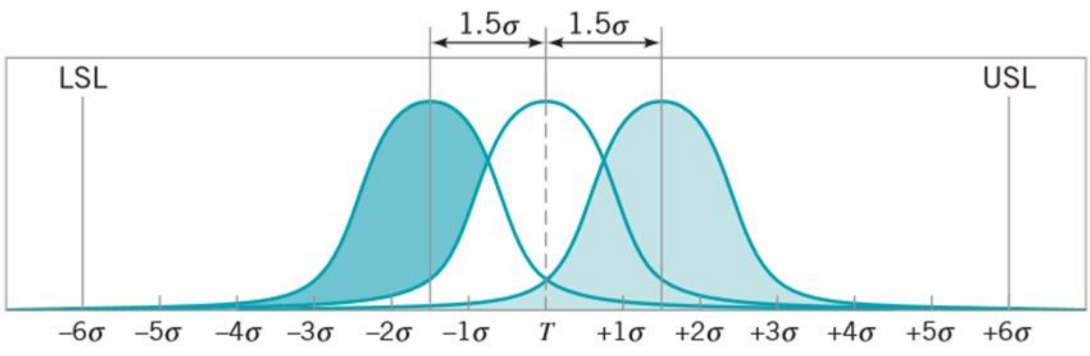

Figure 1. Normal distribution with the mean shifted by ±1.5 (Montgomery, 2009)

According to Park (2003), the process mean is to be kept at the target value in practice. However, the process mean during one time period is usually different from that of another time period for various reasons. This means that the process mean constantly shifts around the target value. To address typical maximum shifts of the process mean Motorola added the shift value ±1.5σ to the process mean. This shift of the mean is used when computing a process sigma level. According to Pyzdek (2003), the process mean can drift 1.5 sigma in either direction. The area of a normal distribution beyond 4.5 sigma from the mean is indeed 3.4 PPM (parts-per-million). Since control charts could easily detect any process shift of this magnitude in a single sample, the 3.4 PPM represents a very conservative upper bound on the non-conformance rate.

There are several approaches to implement Six Sigma, such as DMADV, DFSS and DMAIC (Six Sigma Process Improvement Approach). DMADV methodology is used to have more detectable, completed and clean performance based on creating new product designs or process designs. This methodology consists of five phases: Define Measure, Analyse, Design, and Verify. DFSS is a systematic methodology utilizing tools, training, and measurements to enable the design of products and processes that meet customer expectations and can be produced at Six Sigma Quality levels. Six Sigma for process improvement follows the DMAIC methodology. This methodology was applied in this work according to its five phases: Define, Measure, Analyse, Improve and Control.

2.1.1. DMAIC Methodology

Hoerl and Snee (2010) shows that DMAIC is used by Six Sigma as a generic problem solving methodology that applies across cultures, processes, functions, types of industry. It has developed by using of DMAIC or similar approaches around the world in many different improvement circumstances. DMAIC methodology also has served to improve response time intervals, case solving time and case solving rates. Statistical thinking is a method used as part of DMAIC methodology (Pugna, Negrea et al., 2016).

Aized (2012) has demonstrated that the Six Sigma has a five-phase cycle: ‘Define’, ‘Measure’, ‘Analyse’, ‘Improve’, and ‘Control’ (DMAIC) for process improvement that has become increasingly popular in Six Sigma organizations. According to Sokovic et al. (2005), Six Sigma involves project management for each phase during the improvement.

In the literature, DMAIC methodology is utilized in the surface mount technology to improve part of process, eliminate the defects. Tong, Tsung et al. (2004) has applied DMAIC to improve the capability of SMT solder printing process by approaching large deviations of solder thickness that may cause PCB failure. Tong, Tsung et al. (2004) has implemented the Define-Measure-Analyse-Improve-Control (DMAIC) methodology to improve the capability of the solder paste printing process by reducing thickness variations from a nominal value and also process capability analysis and statistical process control were used to measure and analyse the current printing performance of the screening machines, design of experiment was used to determine the optimal settings of the critical-to-quality factors in the screening process. Typically, the earlier a defect is found in an SMT line, the less expensive the costs are of repairing that defect.

2.1.1.1. Define Phase

In the first phase of six sigma studies, Eckes (2003) has published that the project team is formed, a charter is created, customers, their needs and requirements are determined and verified, and, finally, a high-level map of the current process is created.

The aim of this stage is to define the objective and scope of the problem. The important points that have to be taken into account are:

- The suitability of the selected project to your capability and opportunity;
- Creating a higher quality level or the high probability of cost reduction;
- Defining problems clearly and as much possible as numerical.

2.1.1.2. Measure Phase

In this stage relevant information that defines the existing status by all means is gathered. Eckes (2003) showed that the current sigma performance is calculated, sometimes at a more detailed level than occurred at the strategic level of Six Sigma in the measurement stage, measurement work of the failures that causes the problem is made. In terms of the measurement work, number and ratio of failures are defined and possible consequences are evaluated.

2.1.1.3. Analyse Phase

In the analysis phase, according to Montgomery (2009), the objective is to define the cause-and-effect relationships and to understand the different sources of variability by using data in the process. The reliability of the data is a significant issue in the analysis phase. Therefore, it is necessary to collect correct data before the analysis.

2.1.1.4. Improve Phase

This stage is the one that the defects are eliminated or their effects will be mitigated. According to Eckes (2003), necessary works are done in order to eliminate the causes of defects that cause to problem in the improvement stage. In this phase, the team generates and selects a set of solutions to improve sigma performance. The best solution is chosen by this team to raise the yield in the process.

2.1.1.5. Control Phase

According to Eckes (2003), control phase is the most important stage in Six Sigma methodology. In order to remain the improved sigma level, some techniques are used in the new process shown in:

- The reduced defects in the first four stages are defined;
- It is decided how the defects will be kept under control;
- Even the least successes are ensured to be lasting with the aid of Six Sigma's powerful tools.

2.1.2. Tools of DMAIC Methodology

DMAIC includes a wide range of different tools from Define Phase to Control Phase. As the implementation process of Six Sigma follows DMAIC, the tools can be related to specific phases of the cycle (see Table 1). Different tools are used for different phases and lead to specific results.

Table 1. Six Sigma tools commonly used in each phase of a project (Pyzdek, 2003)

Project Phase	Candidate Six Sigma Tools
Define	☐ Project charter ☐ VOC tools (surveys, focus groups, letters, comment cards) ☐ Process map ☐ QFD, SIPOC ☐ Benchmarking
Measure	☐ Measurement systems analysis ☐ Exploratory data analysis ☐ Descriptive statistics ☐ Data mining ☐ Run charts ☐ Pareto analysis
Analyze	☐ Cause-and-effect diagrams ☐ Tree diagrams ☐ Brainstorming ☐ Process behavior charts (SPC) ☐ Process maps ☐ Design of experiments ☐ Enumerative statistics (hypothesis tests) ☐ Inferential statistics (Xs and Ys) ☐ FMEA ☐ Simulation
Improve	☐ Force field diagrams ☐ 7M tools ☐ Project planning and management tools ☐ Prototype and pilot studies
Control	☐ SPC ☐ FMEA ☐ ISO 900× ☐ Change budgets, bid models, cost estimating models ☐ Reporting system

2.1.2.1. Pareto Chart

Pareto analysis is used to answer such questions as “what department should have the next SPC team?” or “on what type of defect should we concentrate our efforts?” (Pyzdek, 2003).

Montgomery (2009) proves that the Pareto chart is simply a frequency distribution (or histogram) of attribute data arranged by category. Pareto charts are often used in both the measure and analyse phases of DMAIC.

The Pareto chart divides data into the vital few versus the useful many. This is based on the concept of the 80–20 rule. According to Eckes (2003), the importance of Pareto chart is that it is much easier than using other DMAIC tools for Six Sigma project team to reduce the largest contributor.

2.1.2.2. Cause and Effect Diagram

Radhakrishnan (2011) defines cause and effect diagram called as fishbone diagrams can also be useful to identify and analyse potential causes for Service Quality and Production Process issues. It is constructed to analyse the causes that are causing the depth variation. According to Yadav and Sukhwani (2016), the reason for the observation of the cause and effect diagram is that the process is investigated by experts and their aids.

2.1.2.3. Histogram

Eckes (2003) describes histogram as a graphical display of the number of times a given event is seen in a set of observations. According to Eckes (2001), it is not the only graphical tool that shows variation but also shows a variety of graphical tools that exhibit variation.

According to Pyzdek (2003), a histogram displays the numbers in a way that makes it easy to see the dispersion and central tendency and to compare the distribution to requirements. One of the keys of DMAIC is process histogram analysis for special cause or common cause of variation.

2.1.2.4. Analytic Hierarchy Process

Triantaphyllou and Mann (1995) showed that the AHP and its use of pairwise comparisons have inspired the creation of many other decision-making methods. According to Zhang (2010), the basic procedure for AHP approach by the mean of normalized values method is given as following:

- Normalize each column to get a new judgment matrix;
- Sum up each row of normalized judgment matrix to get weight vector;
- Define the final normalization weight vector W.

3. CASE STUDY BACKGROUND

Delphi is one of the largest automotive suppliers delivering advanced electrical and electronic, powertrain and safety technologies to vehicle manufacturers around the world enabling them to make vehicles that are safer, greener and better connected, headquartered in the UK. On this chapter a brief explanation of the group is given followed by a deep explanation of Delphi Automotive from its business to its process details.

The history of Grundig, at that time called "Radio Vertrieb Fürth", began its industrial activity in Portugal in November 1965, producing in its Braga factory the first radio device, a "Transonette 60". The company has suddenly gained a reputation with the development of the legendary radio receiver with great success in the "Heinzelmann" market. Ten years later, Grundig will become the largest radio manufacturer in Europe, selling over a million handsets with more than 10000 employees and becoming a major player in consumer electronics over the years with its pioneering developments.

While the demand side was booming between 1990 and 1991, in 1996 Grundig suffered the worst of its time. Philips broke off its dealings with the Grundig group later this year. Grundig concentrates on the European market by re-establishing its aims and objectives with the acquisition of independence. Braga factory started out as Grundig and was acquired by Delphi in 2003.

Key moments of Grundig/Delphi’s history in Braga :

1965 - Grundig Foundation in Braga

1967- Production of Black and White Televisions

1973 - Production of Car Radios

1978 - Production of the 1st Color Television and Hi-Fi

1988 - Production of Cordless Phones

1990 - Unit specialized in the production of SELF-RADIOS

2003 - Delphi Grundig Partnership

2011 - Delphi Automotive

2015 - Celebrate 50 years Connecting Braga to the World

3.1. Characterization of Delphi Automotive-Braga

The Delphi in Braga is a company that specializes in the manufacture of components for the automotive industry. Currently, it has approximately 700 employees in facilities with a total area of 32921 square meters, of which 9600 square meters correspond to covered buildings (Table 2).

Delphi Automotive-Braga is one of the largest manufacturers of automotive components in the European market and the bulk of the receivers' production volume comes from the Delphi production in Braga, which is very close to the total production of the factory. The main customers are the VW group (Volkswagen, Audi, Seat and Skoda), General Motors (Opel / Vauxhall), the Fiat group (Fiat and Lancia), Daimler-Chrysler, Magneti Marelli, Ford and Volvo. Delphi in Braga produces more than 1.4 million auto radio and 3.2 million antennas per year and holds ISO 9001 (Quality Management System Certification), Acquired in 1994, of ISO / TS 16949 certification (Certification of Quality Management Systems for the automotive industry) and ISO 14001 (certification of Environmental Management Systems) obtained in 2001.

The current production program of the Braga plant includes automotive, communication and navigation systems, antennas and systems for navigation and entertainment. Delphi Braga also uses different methodology for quality management. They believe that only high productions can be improved by using only high quality standards. Thus, they use lean six-sigma, Six Sigma and 5S methodology to sustain their success. Delphi Automotive-Braga also promotes employee training in Six Sigma.

Table 2. Total general number at the company

Area in Complex (m2)	32921
Area in Factory (m2)	9600
Production collaborators	600
Total Employees (Support department)	700
# Customer	70
# Product Destination Locations	109
# Number of different products produced	430
# Number of different shopping items	3899

Delphi in Braga is committed to achieving excellence, with the goal of being recognized by customers as its best supplier, adopting the following principles:

- Delphi focuses on the satisfaction and demand of external and internal customers;
- To recognize employees as our greatest asset;
- To treat everyone with respect;
- To promote teamwork;
- Innovation and continuous improvement are the aim of all employees;
- Protecting interests is more important than correcting mistakes;
- To promote the elimination of waste at all levels;
- Delphi accepts change as opportunity

3.2. Description of Process

The following subsections present the current state of production department, with focus in Surface Mount Technology (SMT). The SMT line is characterized, including the printing process in SMT, which is focused on performance improvement.

3.2.1. Surface Mount Technology (SMT)

Surface Mount Technology is the method which components are mounted directly on the surface of the printed circuit board (PCB), allowing the use of both faces. Electronic components created in this way are called surface mount devices (SMDs). The first operation in the process is loading. SMT process consists of loader, printer, printing inspection, placement, oven, inspection and loader (see Figure 2).

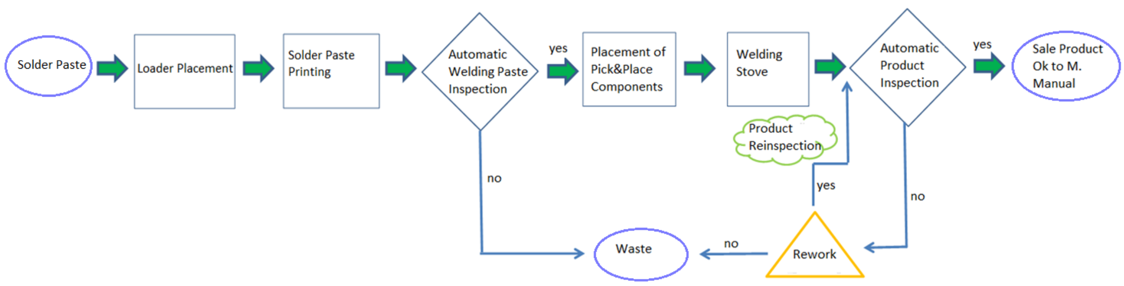

Figure 2. The Printer Flowchart

Since the all operations in SMT constitute a process of connected automatic machines, most of equipment's is operating at the limits of their adjustment. This process enables mass production at a very rapid rate by allowing placement of components to be separated from the actual soldering process, and can run without manual intervention.

Delphi Automotive Systems Portugal strives to use the better existing technology; it is equipped with twelve fully automated SMT assembly lines to quickly and efficiently meet customer requests in line with the customer's expected product requirements. The study is in one of these lines.

SMT process is following these steps:

The canister which includes PCBs prototype is placed in front of loading line. Loading line works automatically (Figure 3). It picks PCB from canister and delivers the board towards the printing machine. The main purpose of the loading is to ensure that each PCB is placed in the operation line properly.

Figure 3. Loading line

The next operation is the solder paste printing (Figure 4) that puts the required paste down on a board and makes a deposition on a pad. This is the first operation which places solder paste on the boards before the component's placement. In the SMT, board and solder paste are defined as inputs, the stencil which is located between proflow and board is used as a material to guide the solder paste to fill the apertures. SMT output is the printed PCB.

Figure 4. Printing machine

The solder paste printing is the first operation inspected in SMT process. Printed board is automatically inspected according to solder paste volume, height, area and position. Before board moving through inspection machine, camera scans the board to learn PCB specifications (Figure 5). The placement of components is critical the solder paste print must be aligned correctly, and the amount of solder paste for each joint must be adequate. For a precise component placement, the pressure must form a flat fold.

Figure 5. Inspection machine

With the Pick & Place method, the components collected in the feeders are placed in the X and Y axes in the loading position predefined by the equipment software (Figure 6). Every feeder has a barcode which the operator associates to the barcode on the reel when it's loaded. This method provides opportunity for part traceability. The operation automatically runs by picking up components and placing them down into the solder paste. The machine can pick up more than one component at one time. In this operation, at least four machine run for placement. Different kinds of components such as small parts, larger parts are placed into the board depending type of the production.

Figure 6. Pick and Place machine

After the placement of components, the placed board goes through the reflow oven to melt solder paste and burn off flux (Figure 7). This process requires a gradual increase in temperature to the melting point and subsequent cooling. Then the solder paste is hardened to bond the components into place and form to electronic connection. This operation is reasonably different from how somebody would solder by hang.

Figure 7. Reflow oven

Automatic product inspection is the last control which the PCB are verified by using optical inspection equipment (AOI), consisting of digital cameras in orthogonal and angular position (Figure 8).

Figure 8. Automatic product inspection

Rework - In case of non-conformities at the checkpoint (IAP), the PCB are analysed and classified by properly trained and certified employees who decide whether there is a possibility of rework or It is a piece of refuse.

3.2.2. Solder Printing Process

One of the most important operation of the SMT process is the application of solder paste to the printed circuit board (PCB) so, this operation is described in detail below (which is referred to as the solder printing process). The aim of this process is to accurately deposit the correct amount of solder paste into each pad to be soldered. It is essential that every pad on every board have solder paste deposit of same and predetermined amount. This is achieved by screen-printing the solder paste through a stencil or foil but also can be applied by printing. Solder paste is applied in pattern using a stencil so that it leaves solder paste only where is necessary to solder the terminal of a device. The solder paste viscosity makes it sticky so that devices can be placed onto the paste and remains held there simply by sticking. It is widely believed that this part of the process, if not controlled correctly, accounts for the majority of assembly defects. The flow chart of printing process is shown in Figure 9.

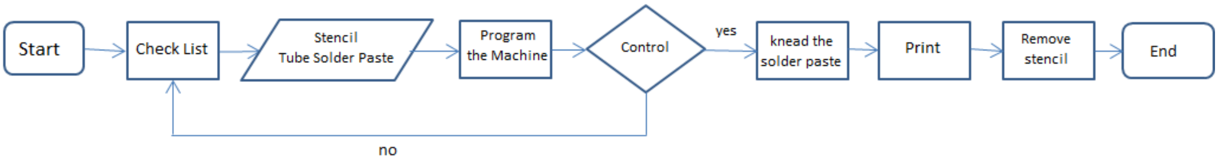

Figure 9. The flow chart of printing process

In the beginning of the process, the checklist including stencil type, printing program and solder paste type is controlled by the operator. Then, solder paste is put in the PCB through the stencil. Since there are different PCBs, the program is adjusted for each board. In order to use the solder paste efficiently, it is kneaded in the machine before the printing. The solder paste is pushed through the stencil to fulfil the gaps. After the printing process, the stencil is removed and the place of the stencil is cleaned. The stencil is cleaned periodically, once per 20 board printings.

4. APPLYING DMAIC PHASES

Printed circuit board (PCB) printing is the one of the crucial processes in SMT. Since the printing process is the previous step before placing the component on the board, the prerequisite for ensuring the correct placement is printing solder paste on the surface of the PCB carefully considering shape, quantity, and coordinate position (X, Y). Industry reports indicate that approximately 50%–70% of soldering defects are attributed to the solder paste printing process for PCB assembly. According to another opinion, solder paste printing is only the first step in the SMT process, and defects usually appear only after reflow soldering. If the printing solder paste inspection does not exist in the process or is not reliable, the process cannot be optimized.

This study focused on improvement of printing process. The main goal is to reduce defect rate, raise the current sigma level in the printing process in order to increase yield. The problem will be addressed using Six Sigma approach with help of DMAIC methodology.

4.1. Define Phase

According to company strategy, it was decided to work on performance of the printing process. The define phase, initially describes the major problem that affects the performance of process. In order to detect the defects that may cause PCB failure, all types of defects were collected. In the inspection machine, there are many identified defects occurred during printing process. Therefore, the company has accepted these defects which are identified by inspection machine as a problem that should be reduced.

There are two kind of rejected PCBs at the automatic optical inspection machine: true defectives and false defectives (assessed by human operator). This corresponds to the alfa error or type I error, consisting of erroneously classifying as defective a good PCB. If the operator decides that the PCB is good even although the result of inspection is false in the PCB is counted as a good printed. Thus, they do not waste time.

Otherwise, system would have slowed down to analyse each defect. However, operators sometime can make a mistake. They sometimes approve the defects which is not acceptable for the further process. This situation leads to produce faulty PCB. Consequently, it is difficult to control the operator-to-operator variation in determining the solder paste defects. PCBs are not considered which is permitted by the operator to pass the other process despite being defective in this study.

The standard limits and parameter values for printing process depend on the printing line, supplier recommendations and customer requirements. Tolerance limits are defined for each type of defect.

Moreover, description of the defects is an important way to predict further threats. In this case, the types of defects are defined considering volume, position, bridging, height and area of solder paste deposition on each pad. These characteristic of defects are described in the following section.

4.1.1. Volume

Volume corresponds to the amount of solder paste deposit in each PCB pads. For each one there is a definition of the nominal value and specification. Therefore there is not only one definition of volume but also different volume levels exist in the program according to each pad. The volume defects are divided into two types: excessive and insufficient.

Excessive is the defect that extra solder paste excesses the pads dimension and the respective specification limit (much more than target amount). It may occur due to over pressure or lack of proper setting. In order to diagnose the error, volume of solder paste is examined. In the screening process, the solder paste volume transferred on the PCB is the most important factor that needs to be controlled. This is the error when uniformity of paste volume is changed across pads.

In the process, the inspection machine controls the volume of solder paste after printing process whether it is between proper values. An example is shown in Figure 10. The dialog box presented uses 100% to correspond to the nominal /target values and considers all volumes as a percentage of this reference value. The second dialog box (in Figure 10) presents minimum and maximum volume values defined by machine and result of volume value after solder paste printing process.

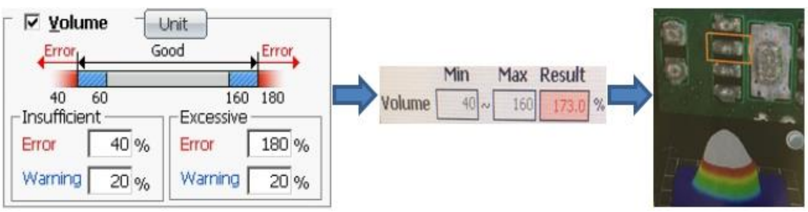

Figure 10. Appropriate limits for excessive volume and error that occur

As an example, Figure 11 shows PCBs with amount of solder paste volume above upper specification limit.

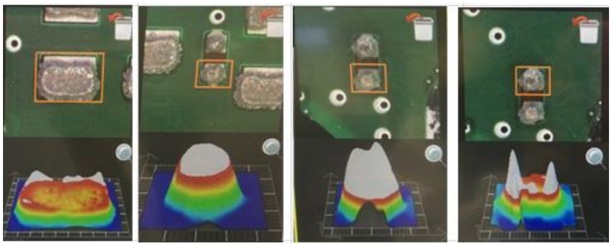

Figure 11. Excessive Volume Errors in Stencil Printing Process

Insufficient amount of solder paste is described as: the amount of solder paste deposited on PCB at printer station is less than stencil opening design or, after reflow, insufficient solder to form a fillet at the component leads. When the solder paste falls below minimum level of volume (examples are shown in Figures 12 and 13), inspection machine give detects this defect.

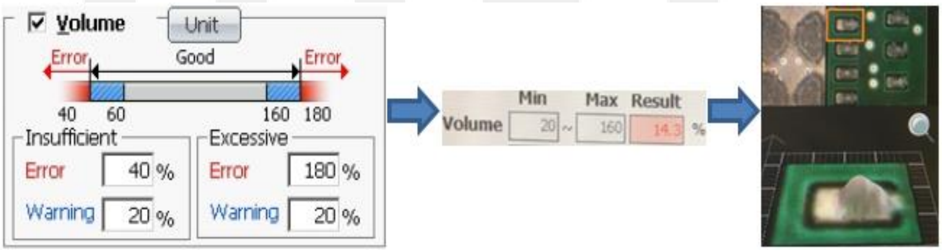

Figure 12. Appropriate limits for insufficient volume and error that occur

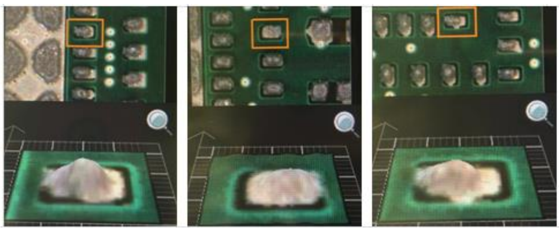

Figure 13. Insufficient Volume Errors in Stencil Printing Process

4.1.2. Position

Position defect is defined as the solder paste that is deposited in an inaccurate position instead of at the pre-defined coordinates. The coordinate position (X, Y) in the inspection machine is used to produce an accurate coordinate map of the paste, pad and surrounding area.

The positions are calculated by measuring the distance from beginning of centre of each pad. There is a tolerance limit for X and Y offsets for each pad, which is an acceptable value. X and Y offset failures are evaluated separately. Figures 14 and 15 provide examples of position definition limits and errors.

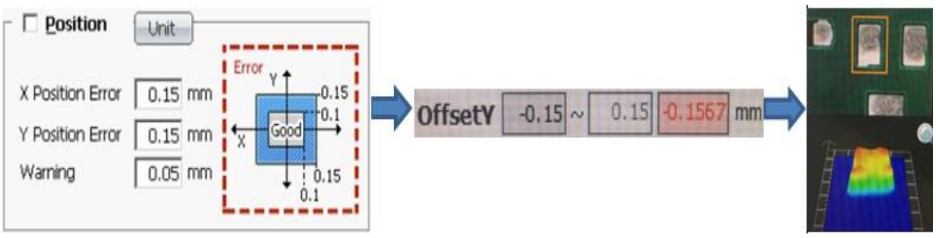

Figure 14. Appropriate limits for position and error that occur

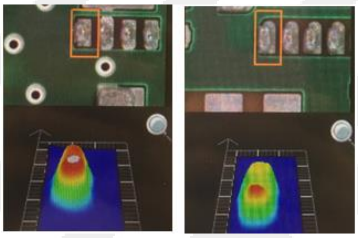

Figure 15. Position Errors in Stencil Printing Process

4.1.3. Bridging

Solder bridging is a common defect on a PCB, which occurs when the solder forms an abnormal connection between two or more adjacent pads to form a conductive path. 'Bridging' can be a result of poor board support or stencil condition/cleanliness. This defect can be microscopic in size and extremely hard to detect. If it goes undetected, it can cause serious damage to the circuit assembly, like a burn-up or blow-up of a component and/or burn-out PCB trace. In the inspection process, bridge height and distance between pads are described. The print alignment, or the alignment of the stencil to the PCB pad design, may be slightly off. Bridging can also be caused from too much solder paste being deposited.

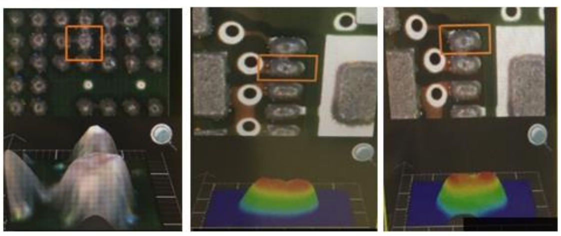

Figure 16. Bridge Errors in Stencil Printing Process

4.1.4. Heigh

The calculation of solder paste height is related to stencil thickness and its thickness times the aperture size. Heigh defect occurs when its value is outside specification limits. According to height of solder paste, there are two limits defined as upper and low.

Upper height error occurs when deposited solder paste height exceeds standard height value. When the paste height reaches the upper level and over tolerance, system perceives the defect. As can be seen in Figure 17, there is also tolerance limit which is endurable value for soldering process.

Figure 17. Appropriate limits for upper height and error that occur

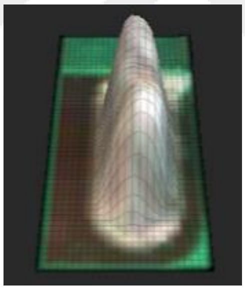

Figure 18. Upper Height Errors in Stencil Printing Process

Contrary to upper height failure, lower height is a defect that reveals when the solder height is lower than expected. Only lower level is controlled to describe this defect. When the solder paste height goes down below 250 um, it is defined as an error. Tolerance limit is the same with upper limit.

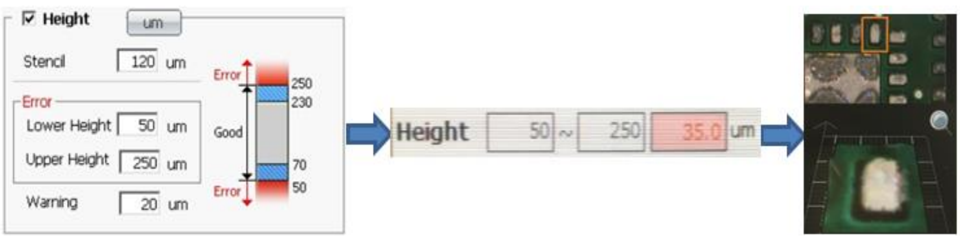

Figure 19. Appropriate limits for lower height and error that occur

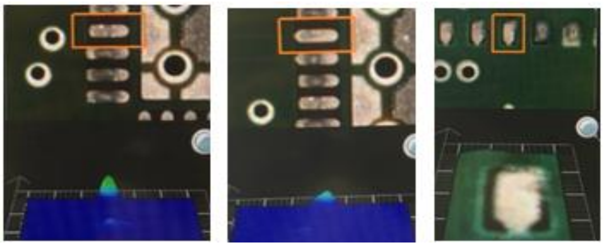

Figure 20. Lower Height Errors in Stencil Printing Process

4.1.5. Area

The solder paste must be enclosed on a specific area. One important issue to use the stencil for printing process is to provide stable area in the pad. High area defects occur on the board when the solder paste is out of area which is defined in the inspection machine in the printing process; the area is regarded as size of the stencil hole.

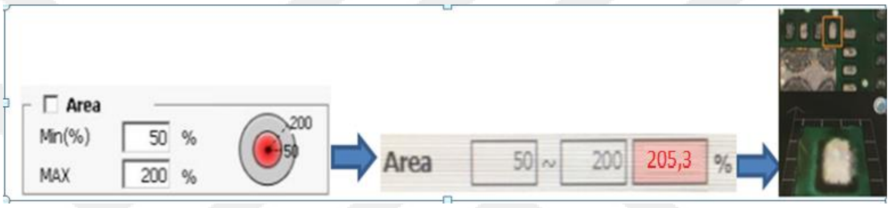

Figure 21. Appropriate limits for high area and error that occur

Figure 22. High Area Errors in Stencil Printing Process

If the area of solder paste is less than the minimum percentage, the result of inspection shows that it’s low area error. Minimum percentage of area varies by pad area.

Figure 23. Appropriate limits for low area and error that occurred

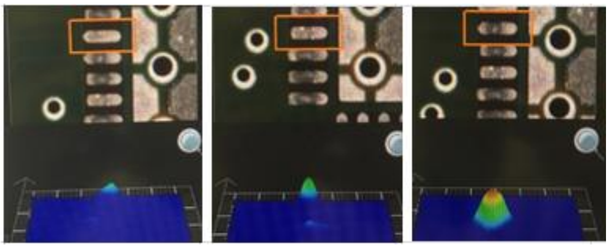

Figure 24. Low Area Errors in Stencil Printing Process

It has been clarified that these defined defects lead to problems in the process. These defects are used in the analysis and measurement phases which error has more influence on the process. The project charter was created in define phase (Table 3).

Table 3. Project Charter of Printing Process

<table>
<tr><td colspan="2">Project Charter</td></tr>
<tr><td colspan="2">Project Name: DMAIC Approach to Solder Paste Printing in Printed Circuit Boards.</td></tr>
<tr><td colspan="2">Problem Statement & Objective: Defects cause low performance in the printing process. DMAIC cycle is used to improve the solder paste printing process of Printed Circuit Boards (PCBs) in surface mount technology (SMT). The purpose of project is to focus on the reducing of defect rate in the process.</td></tr>
<tr><td colspan="2">Business Case: In the case study, solder paste defect is defined as the most common type of defect occurred in the process. The used method (proflow) can be compared with new selected method (squeegee) using statistical analyses.</td></tr>
<tr><td rowspan="3">Team Members:
Fernando Guedes
Jorge Goncalves
Diogo Leitão
José Machado
Beyza Nur GİDER (SEZGİN)</td><td>Project Area: Delphi Automotive-Braga SMT Line / Solder Paste Printing Process</td></tr>
<tr><td></td></tr>
<tr><td>Duration: 1/3/2017 - 15/7/2017</td></tr>
</table>

4.2. Measure Phase

By the Measure phase of the study, it was decided to calculate sigma level to assess process performance relative to the defect specifications established in the Define phase. Once specifications were correctly established, it was fairly simple to determine what the defect is relative to those definitions.

In order to compare the error rates of different products of different complexity, a common combination is needed, so the error rate is calculated on the occasion of comparing systems of different complexity. In comparison of defects, Sigma level statistically gives clue about what is the biggest root defect in the production process.

Also, one of the important issue is a collection plan which was adopted for the data to be gathered efficiently. Determining sigma levels of defects allows process yield to be compared throughout an entire organization. The defect needed to reach Six Sigma performance levels depends on the organization's starting point and their level of commitment.

When dealing with nonconformities or defects, defects per unit (DPU) statistic is often used as a measure of capability, where:

$$DPU = \frac{Total\ Number\ of\ Defect}{Total\ Number\ of\ Unit} \tag{1}$$

In the process, DPMO is a measure of process performance. A widely used way to do this is the defects per million opportunities (DPMO) measure formulated as:

$$DPMO = \frac{Number\ of\ Defect \times 1000000}{\text{Number of Unit} \times Number \text{ of Opportunities Per Units}} \tag{2}$$

To calculate sigma level using the discrete method, three items are used in the formula:

- Units: The unit is something that is delivered to a customer and can be evaluated or judged as to its suitability.
- Defects: Any event that causes error in the process or does not meet the customer's satisfactions.
- Opportunities: Opportunities are the number of potential chances within a unit for a defect to occur.

In the problem, there is numerous type of board which are printed in the printing machine and are control in the inspection machine. Products with many components typically have many opportunities for failure or defects to occur. It is important to be consistent about how opportunities are defined, as a process may be artificially improved simply by increasing the number of opportunities over time. Accordingly, the type of board was considered as a number of units. The PCB contains thousands of pads and each pad is meticulously printed by printing machine. Number of pads in PCB was used in DPMO formula as an opportunity. Consequently, the unit is number of total pads which are painted in printing process and can be evaluated as to its suitability.

The sample size is statistically critical point that decides accurate data to measure and then analyse correctly. Since there were multi various type of production in the process, one of the lines was selected to evaluate the data. This was the substantial way that analyses and measures of similar type of products so that obtain certain result. Therefore Line 22 one of SMT process was observed during the study.

In this phase, Sigma level for each type of defect was calculated to measure the process quality level. Defects data were collected for 10 days in April and 35503890 pads were inspected. As a result 9123 defects were found. The data and the sigma values calculated for each type of defect (see Appendix I – Sigma conversion Table) is shown in Table 4.

Table 4. Initial Sigma level

	Volume	Position	Bridging	Height	Area	Total
Number of Pads Rejected	8629	95	380	15	4	9123
Total Number of Pads	35503890	35503890	35503890	35503890	35503890	35503890
DPMO	243.04	2.67	10.70	0.10	0.42	256.96
Sigma Level	5.0	Over 6	5.7	Over 6	Over 6	5.0

In the calculation, since the type of pads might be different from each type of board, number of opportunity was corresponding to number of pads in PCB. According to printing process data in February, 5 type of board were observed and evaluated that were used as an opportunities. These defect factors were quality level, which was measured through DPMO, and the Sigma level of the process. The total defect number is the rejected number of pads in the inspection process. As the DPMO calculation is for each type of defect, number of defective pads was summed for each board.

Sigma level calculation for the Volume defect:

$$DPMO_V = \frac{8629 \times 1000000}{35503890} = 243{,}04$$

$$\sigma_V = 5$$

Position sigma level calculation:

$$DPMO_P = \frac{95 \times 1000000}{35503890} = 2{,}67$$

$$\sigma_P = Over\ 6\ sigma$$

Bridging sigma level calculation:

$$DPMO_B = \frac{380 \times 1000000}{35503890} = 2{,}67$$

$$\sigma_P = 5{,}7$$

Height sigma level calculation:

$$DPMO_H = \frac{15 \times 1000000}{35503890} = 2{,}67$$

$$\sigma_H = Over\ 6\ sigma$$

Area sigma level calculation:

$$DPMO_A = \frac{4 \times 1000000}{35503890} = 2{,}67$$

$$\sigma_A = Over\ 6\ sigma$$

Total sigma level calculation:

$$DPMO_T = \frac{9123 \times 1000000}{35503890} = 2{,}67$$

$$\sigma_P = 5$$

According to calculation, the results demonstrated that the lowest sigma level is 5 in volume defect. The highest DPMO value was occurred in this defect. This approach shows that if the number of errors is high, the DPMO value is high and the sigma level is low. In shape, area and height defects which the highest sigma level was obtained as over 6 sigma level, the DPMO value was the lowest value comparing with other type of defects.

As the result of defect sigma levels were not at expected level, defect rate would be reduced. The lowest value of sigma levels calculated in the formula was found as 5 level of volume defect. According to the sigma levels; volume was major type of defect which had contributed to the PCB to be rejected by the operation.

Pareto analysis (Figure 25) showed that volume defect is the most frequent type of defect, representing 94.6% of total defects occurred in solder printing process.

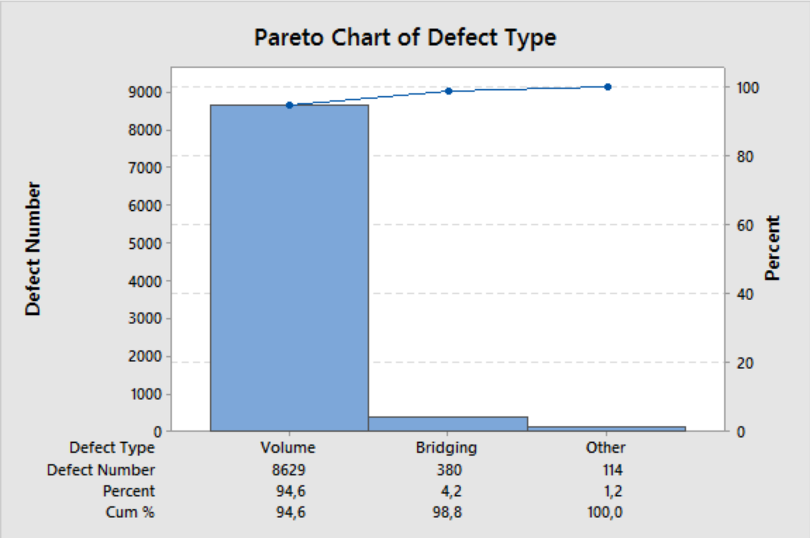

Figure 25. Pareto analyse of defect number

4.3. Analyse Phase

In the analysis phase, the objective is to use the data from the measure phase to begin to determine the cause-and-effect relationships in the process and to understand the different sources of variability. Analyse phase apply many methods to evaluate the data. One statistical way is conducted to identify the critical factors that influence the solder printing process and improve quality and performance. By this way, previous defined criteria were investigated and evaluated.

Most teams which implement Six Sigma use a combination of data analysis and process analysis to arrive at root causation. The true discovery of why the problem exists is uncovered in Analysis (Eckes 2001). In this study, data analysis focused on addressing major defect by using statistical, exploratory and descriptive tools to guide the analysis. There are many tools that are potentially useful in analyse phase. Analytic Hierarchy Process (AHP) which analyses the possibilities of decision making to overcome the multi-criteria decision with respect to issue was applied for prioritizing the type of defects.

Previously, in the measure phase, operation sigma level demonstrated that it could be improved to reach 6 sigma level which is company’s goal. The performance level of the current process is unsatisfactory and need to be enhanced. According to sigma levels, the result showed that volume defect might be the major error in the studied process. The following method was used to clarify the most critical defect importance in the process.

First, the scale definition was created for pairwise comparison and is illustrated in Table 5 and decision-making using AHP scripting language in Table 6. A pairwise comparison matrix was created based on the cost of defect in the process. In this study, the key criterion used was cost, because it was considered that was the basic constraint to scale defects. According to the effect of defects on the cost of process, the scales were assigned for each defect in the AHP. The survey has done by operators according to pairwise comparison matrix. Operators selected the number for each comparison considering AHP scripting language.

Table 5. Pairwise comparison matrix

Relative Effectiveness Scale																		
Parameter	9		7		5		3		1		1/3		1/5		1/7		1/9	Parameter
Volume																		Position
Volume																		Bridging
Volume																		Height
Volume																		Area
Position																		Bridging
Position																		Height
Position																		Area
Bridging																		Height
Bridging																		Area
Height																		Area

- 9 Extreme Favors
-7 Very Strong Favor
-5 Strongly Favors
-3 Slightly Favors
-1 Equal
-1/3 Slightly Favors
-1/5 Strongly Favors
-1/7 Very Strong Favors
-1/9 Extreme Favors

Table 6. Decision-Making using AHP scripting language

AHP Scale of Importance for comparison pair (a_{ij})	Numeric Rating	Reciprocal (decimal)
Extreme importance	9	1/9
Very strong to extremely	8	1/8
Very strong importance	7	1/7
Strongly to very strong	6	1/6
Strong importance	5	1/5
Moderately to strong	4	1/4
Moderate importance	3	1/3
Equally to moderately	2	1/2
Equal importance	1	1

The comparison matrices were circulated among the technical staff and operators of the printing operation. Each respondent was required to choose one of the alternatives listed in Table 5. Therefore, this method conducted pairwise comparisons across all possible combinations of parties.

Since there were five comparisons matter, 5 by 5 matrix was made and then the diagonal elements of the matrix were defined as 1, because the same defect type were not able to compare. The upper triangular matrix was filled up. According to survey result, if the judgment number was on the right of 1, the numeric rating was put on the matrix (Table 7). Otherwise, if the judgment number was on left of left 1, the reciprocal value was put on the matrix following;

$$\begin{bmatrix} 1 & 9 & 1/5 & 1 & 4 \\ 1/9 & 1 & 1/7 & 1/7 & 1/2 \\ 5 & 7 & 1 & 7 & 8 \\ 1 & 7 & 1/7 & 1 & 4 \\ 1/4 & 2 & 1/8 & 1/4 & 1 \end{bmatrix}$$

Table 7. Pairwise comparison matrix of the main criteria with respect to the goal

	Volume	Position	Bridging	Height	Area
Volume	1	9	0.2	1	4
Position	0.11	1	0.14	0.14	0.50
Bridging	5	7	1	7	8
Height	1	7	0.14	1	4
Area	0.25	2	0.13	0.25	1
Total	7.36	26	1.61	9.39	17.50

In order to normalize the matrix, each column of the reciprocal matrix was summed and then each element of the matrix was divided with the sum of its column. In this relative weight were normalized and the sum of each column were corresponding to 1 following Table 8.

Table 8. Calculation sum of all elements in priority vector 1

	Volume	Position	Bridging	Height	Area
Volume	0.14	0.35	0.12	0.11	0.23
Position	0.02	0.04	0.09	0.02	0.03
Bridging	0.68	0.27	0.62	0.75	0.46
Height	0.14	0.27	0.09	0.11	0.23
Area	0.03	0.08	0.08	0.03	0.06
Total	1.00	1.00	1.00	1.00	1.00

$$\text{Weight} = \frac{1}{5}\begin{bmatrix} 0{,}14+0{,}35+0{,}12+0{,}11+0{,}23 \\ 0{,}02+0{,}04+0{,}09+0{,}02+0{,}03 \\ 0{,}68+0{,}27+0{,}62+0{,}75+0{,}46 \\ 0{,}14+0{,}27+0{,}09+0{,}11+0{,}23 \\ 0{,}03+0{,}08+0{,}08+0{,}03+0{,}06 \end{bmatrix} = \begin{bmatrix} 0{,}19 \\ 0{,}04 \\ 0{,}55 \\ 0{,}17 \\ 0{,}05 \end{bmatrix}$$

In order to calculate the CR the Principal Eigen value (λ_{max}) was obtained from the summation of products between each element of Eigen vectors and the sum of columns of the reciprocal matrix.

$$\lambda_{max} = (7{,}36 \times 0{,}19) + (23 \times 0{,}04) + (1{,}93 + 0{,}55) + (7{,}40 \times 0{,}17) + (15{,}20 \times 0{,}05)$$

$$\lambda_{max} = 5{,}37$$

Thus for λ_{max} = 5.37 and n=5 (five comparisons), the consistency index (CI) is calculated as follows:

$$\text{CI} = \frac{\lambda_{max} - n}{n-1} \quad (3)$$

$$\text{CI} = \frac{5{,}37 - 5}{5-1}$$

$$\text{CI} = 0{,}092$$

Random index (RI) which is determined from a lookup table (Table 9).

Table 9. Random Consistency Index (RI)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Then, Consistency Ratio, is given by equation 4.

$$\text{CR} = \frac{CI}{RI} \quad (4)$$

$$\text{CR} = \frac{0{,}092}{1{,}12}$$

$$\text{CR} = 0{,}092$$

The value of Consistency Ratio is smaller 10%, the inconsistency is acceptable

Table 10. Defect weight of printing process

Type of Defects	Quantity of Defect * Weight	Cumulative Count	Cumulative (%)
Volume	1624.33	1624.33	88.22
Bridging	210.65	1834.98	99.66
Position	3.53	1838.51	99.85
Height	2.49	1841	99.99
Area	0.22	1841.22	100.00

The Pareto analysis shown in Figure 26, based on data from Table 10, illustrates the list of defects occurring in the concern, which reveals that volume and bridging are the two critical defects with cost weight. The successive phases have concentrated on identifying the major root causes that contribute to the rejection rate.

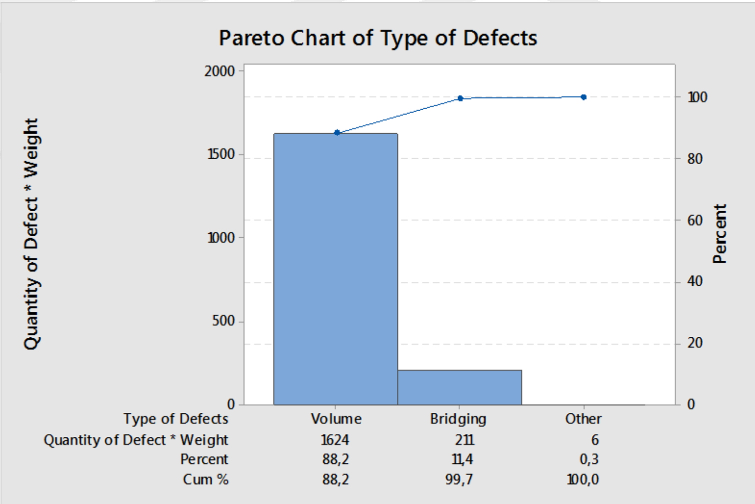

Figure 26. Pareto analysis of “quantity of defect * weight”

The root cause that impacts volume defect should be identified and analysed, so that process improvement can be done in respective areas. In this case, cause and effect diagram supported by brainstorming sessions and mind maps representation was done to identify possible causes of the volume defect, rather than just one of that are most obvious.

Based on the detailed Fishbone diagram, the project team members discussed factors that may cause a volume defect by using brainstorming, and summarized all the factors in the cause-and-effect diagram. Figure 27 shows the Fishbone diagram of this project.

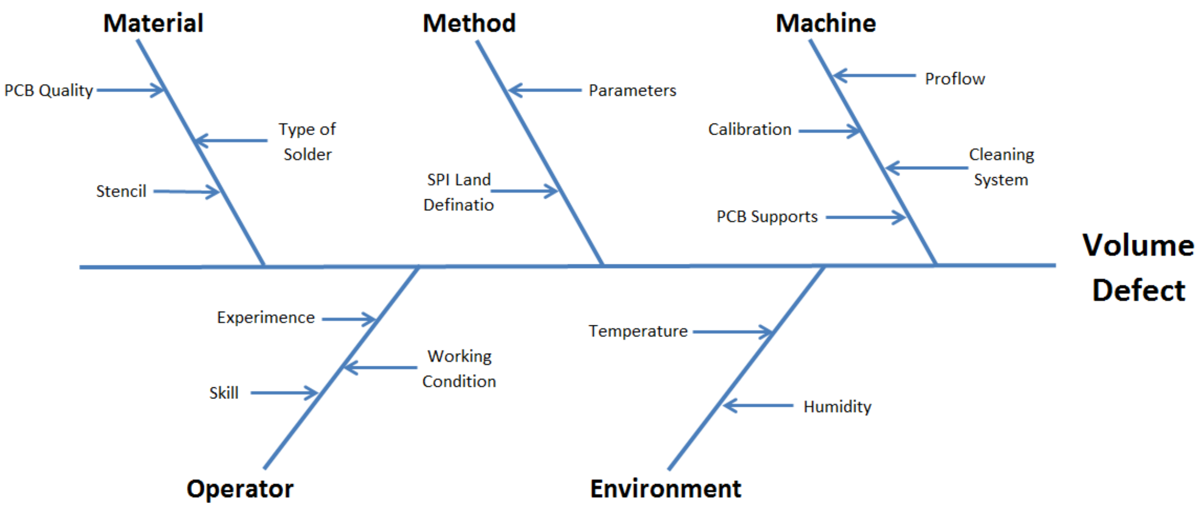

Figure 27. Cause and effect diagram for volume defect

It was decided that the root cause in the process is Proflow. This is the printing method (Figure 28) that the solder tube is attached to print carriages and is used to print various high viscosity materials which display non Newtonian characteristics based on pressure.

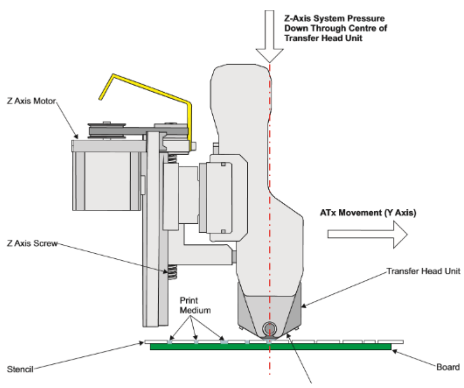

Figure 28. Proflow printing method

Proflow operates in the Y and Z axes. The unit is raised and lowered to screen by means of the special proflow print head mechanism stepper motor. The horizontal movement driven by the machine print carriage motor moves the unit across the stencil in forward and backward direction. A print cycle may consist of a single movement in Y axis. Paste pressure, is applied to the piston crosshead exerting a force onto the print material which forces print material into the proflow conditioning chamber and into the stencil aperture (see Figure 29).

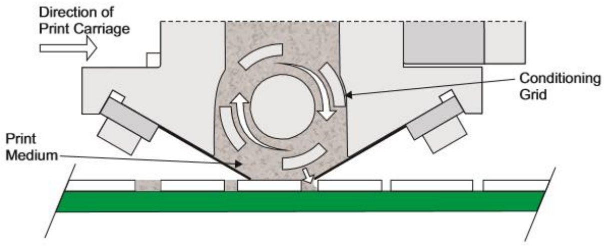

Figure 29. Proflow print medium and Conditioning Grid

The system pressure is a programmable parameter that controls the contact pressure of the transfer head against the stencil. As the transfer head moves across the surface of the stencil, it must have enough downwards pressure. As the unit moves across the stencil, the trailing wiper within the transfer head lifts the print material from the stencil surface creating a rolling movement of material within the conditioning chamber.

The volume of material under pressure from the piston crosshead is kept at constant level within the chamber. In the improve phase, this method will be changed.

During the print process the rotation of the conditioning grid, working together with the print medium pressure, forces print medium into the stencil’s apertures. This is the most significant characteristic of proflow that is the way of deposition into the aperture of stencil.

Due to root cause of defects, it was decided to analyse proflow process in different aspect. The main purpose of the analysis is to compare proflow method to new printing method. The company has decided that there is a problem in the process due to this method. Therefore, this method will be compared with different way of solder paste printing by observing the effects on the volume defined as the highest error rate in the previous step.

The comparison was implemented in the same environment conditions such as temperature, humidity, noise, time, material lots. One type of PCB, stencil and four different types of pins were examined in experiments regarding volume. Each experiment will be examined to understand the difference between proflow and squeegee. Production Line 22 was decided to work on this analysis. The line has been worked with both proflow and squeegee methods. PASW Statistic 18 and Minitab statistical software were used to analyse the difference between two printing methods.

The data used in statistical software was retrieved from inspection machine. This data includes time, component ID, size X and size Y, volume, method type (status) and pin number. The type of PCB used in this experiment is VW MIB*441A. This PCB contains 4457 pads. The pad is a point on the PCB where the solder paste is deposited. Printed paste on the pads is melted and bonded the components. The top of the PCB part was considered to evaluate. Different numbers of pads are used for each component. Additionally, in order to examine volume effects on the pads, different pads size was considered such as the smallest, the biggest and the middle size.

In the printing process, specialists have experience in analysing volume defects. The ability to detect this defect and the associated cost (of repair or scrap) depends of the violated specification limit. The optimal amount of volume is defined for each pad in Delphi Automotive-Braga. The company uses one 3D inspection machine to perform this task in real time and good PCBs are sent to the next process.

The optimal volume value is calculated by using the pad length, width and the stencil height. The height of the stencil (which is an auxiliary tool that forms the painting area between the board and the solder paste) is used in the volume calculation.

If the volume value is outside specification limits is classified as defect by the AOI machine. These limits are defined as volume percentage relatively to the optimal volume value (100%). The amount of solder paste volume to avoid defects is between 40% and 180%, i.e., the amount of solder paste is between this range, the printing process is accepted as Good. However, there are some problems regarding some values within these specifications. Even though PCBs have the value to go through the following process, a specific optimum level is determined in order to avoid problems at further stages. Due to this reason, amount of volume definition on the pads was separated in five specifications as insufficient, low sufficient, optimal, high sufficient and excessive. The values of the ranges are shown in Table 11.

Table 11. The value of the ranges

Range	Amount Type	Impact on Quality
0% - 40%	Insufficient	Defective
40% - 80%	Low Sufficient	Slightly Good
80% - 120%	Optimal	Very Good
120% - 180%	High Sufficient	Good
>180%	Excessive	Defective

The company's experience showed that having a "high sufficient" volume is slightly better than a "low sufficient" volume. There are reasons to support this difference:

- Potential problems caused by "High sufficient" amount of volume are more detectable than "low sufficient" at subsequent processes;
- "Low sufficient" amount needs more control effort than "high sufficient" amount of volume and causes more costs;
- Even though the "high sufficient" amount of solder paste causes more cost due to deposition flux, it leads to less cost than "low sufficient".

In the following statistical analysis, the very good and good result will be considered as an "optimal" range or "high sufficient" range to compare difference and find the better solutions.

4.3.1. Experiment 1

In the first experiment, U29 component as analysed, as the component contains the smallest pads (Figure 30). The pads are aligned horizontally and vertically around the component. The horizontally aligned pad size is 0.7 mm x 0.18 mm. The vertical aligned pad size is 0.18 mm x 0.7 mm.

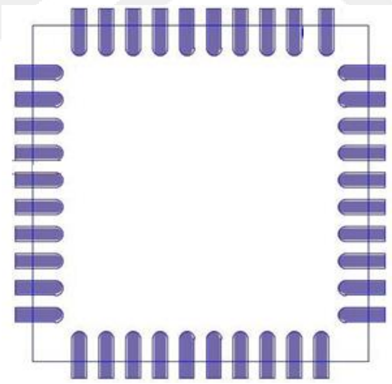

Figure 30. U29 type of component

The data obtained through proflow method (April 3rd, 4th, 5th, 6th) and the other data obtained through squeegee method (April 20th, 21st, 25th, 26th, 27th) were gathered for statistical analysis. The number of proflow data is 216160 and the number of squeegee data is 188654.

Likert type scale was used in the process to ease expressing different analysis, because 5 different amount of solder paste are used as test variable. Results were evaluated by using PASW Statistics 18 which is the last version of SPSS program. The process capability values were displayed by using Minitab 17 statistical software.

In the first observation; regarding to the data, 99.4% of data are good and 0.6% of data are error by using proflow method, while 99.9% of data are good and 0.1% of data are error by using squeegee in printing process (Table 12).

Table 12. Distributions of error and good data according to method type for U29

Method Type	Good/Error	Frequency	Percent	Valid Percent
Proflow	Good	214822	99.4	99.4
	Error	1338	0.6	0.6
Squeegee	Good	188527	99.9	99.9
	Error	127	0.1	0.1

The volume ranges which were defined before analysis were shown in Table 11. The first important observation is that optimal range in the squeegee method is more frequent than proflow method.

When the proflow printing method is used in process 0.6% amount of volume is “insufficient”, 94.2% amount of volume is “low sufficient”, 5.2% is “optimal” and only 1 solder paste is “high sufficient”.

When the squeegee printing method is used in process 0.1% amount of volume is “insufficient”, 26.2% amount of volume is “low sufficient”, and 73.7% is “optimal”. Additionally, there are 12 excessive and 35 high sufficient amount of volume in the squeegee method (Table 13).

Table 13. Distributions of error and good data according to method type

Method Type	Amount of Volume Range	Frequency	Percent	Valid Percent
Proflow	Insufficient	1338	0.6	0.6
	Low Sufficient	203606	94.2	94.2
	Optimal	11215	5.2	5.3
	High Sufficient	1	0.0	0.0
Squeegee	Insufficient	115	0.1	0.1
	Low Sufficient	49400	26.2	26.2
	Optimal	139092	73.7	73.7
	High Sufficient	35	0.0	0.0
	Excessive	12	0.0	0.0

The descriptive statistics are shown in Table 14. The method types are separately indicated as a proflow and squeegee for comparison. According to mean numbers, it is demonstrated that squeegee deposits 16% more solder paste on the pads than proflow (Table 14). Since the range of standard deviations is slightly different between methods, Cp value is calculated to observe difference. The lower limit was defined as 40%, and the upper limit was defined as 180%. The process capability of proflow is 2.928 and the average of volume has reached out to lower limits. The process capability for squeegee is 3.284. Cp value in both methods are bigger than 1.33. Squeegee method is between upper and lower limits. However, proflow method barely fell under lower limit (Figure 31).

Table 14. The descriptive statistic of proflow and squeegee for U29

Method Type	N	Minimum	Maximum	Mean	Standard Dev.
Proflow	216160	11.29	131.70	67.76	7.969
Squeegee	88654	6.31	242.95	83.92	7.106

Additionally, the machine regulation was stable during analysis. Both printing methods have got the same parameters and adjustments.

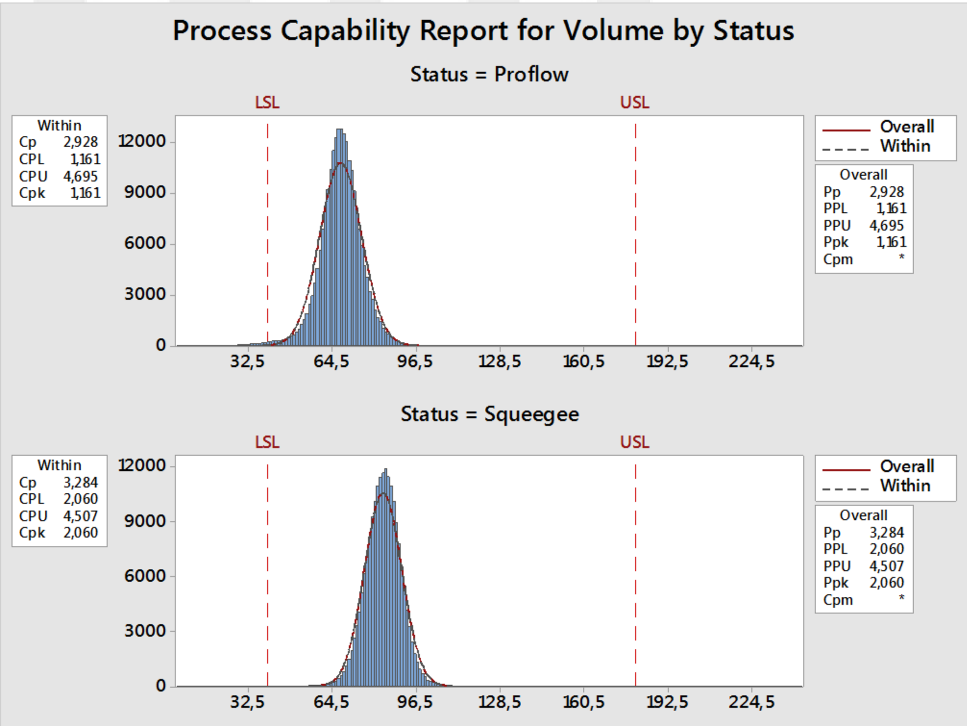

Figure 31. Process capability of Proflow and Squeegee for U29

4.3.2. Experiment 2

In the second experiment, C152 component was examined in the statistical analysis. This component contains two similar pads (Figure 32). The pad size is 5.3 mm x 1.7 mm.

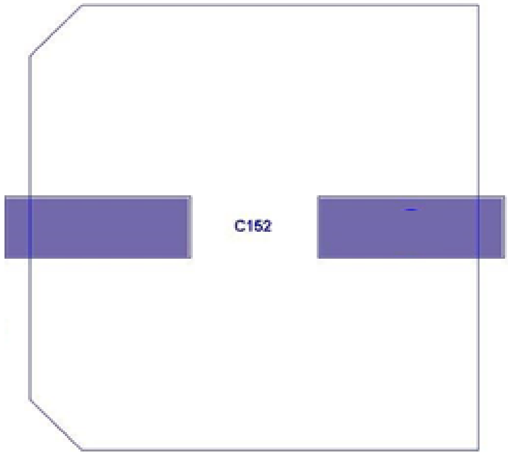

Figure 32. C152 type of component

In the first step for analysis, data of proflow on 3rd, 4th, 5th and 6th of April was collected from inspection machine. Five days data (April 20th, 21st, 25th, 26th, 27th) was collected from the squeegee method. The number of proflow data is 10808, the number of squeegee data is 9438.

According to frequency result in Table 15, almost data are good by using squeegee method, while 99.8% of data are good and 0.2% of data are error by using proflow in printing process. It was observed that squeegee method does not cause error in the process.

Table 15. Distributions of error and good data according to method type for C152

Method Type	Good/Error	Frequency	Percent	Valid Percent
Proflow	Good	10790	99.8	99.8
	Error	18	0.2	0.2
Squeegee	Good	9437	100	100
	Error	1	0.0	0.0

The standard deviation range between proflow and squeegee is an acceptable value. The mean values of both methods are among the values considered as optimal values (80% - 120%). However, using the method squeegee can achieve 18.5% more volume then proflow method (Table 16). It might be proved that sgueegee is better than proflow based on more volume for high performance. It was also shown in the graph by using Minitab.

Table 16. The descriptive statistic of proflow and squeegee for C152

Method Type	N	Minimum	Maximum	Mean	Standard Dev.
Proflow	10808	77.31	269.23	97.55	6.968
Squeegee	9438	79.50	191.56	116.04	3.340

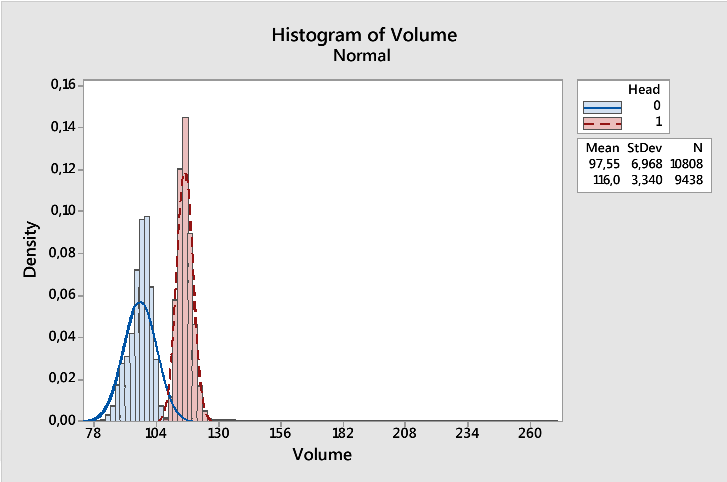

Figure 33. Standard variation of volume considering status for C152

In Figure 33, head 0 represents proflow method, and head 1 represents squeegee method. This situation shows that the printing methods deposit efficiently solder paste into pads which are placed under the C152 component. As shown in Figure 34, Cp value in squeegee printing method is much better than proflow printing method.

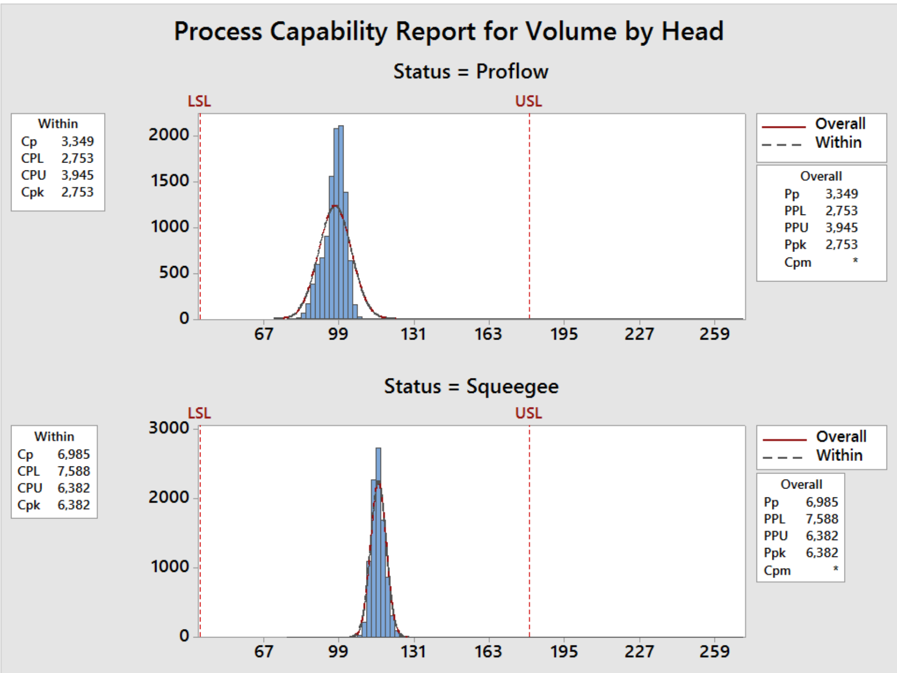

Figure 34. Process capability of proflow and squeegee for C137

4.3.3. Experiment 3

In the third experiment, the C137 components number was analysed in the process. This component consists of two pins and pin size is 1.7 mm x 5.3 mm (Figure 35). There is only one difference between C152 and C137 as a position.

Because, there are two pins which are vertical align on the C137 component besides C15 component type.

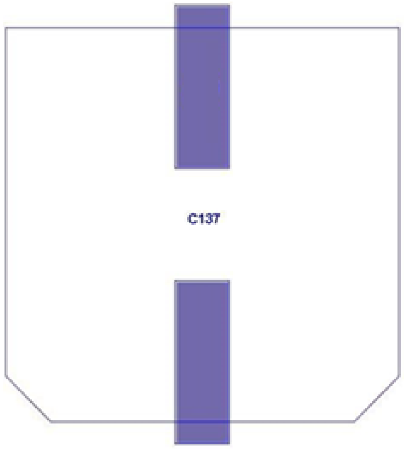

Figure 35. C137 type of component

The data was retrieved from inspection machine which involves both squeegee (April 20th, 21st, 25th, 26th, 27th) and proflow (April 3rd, 4th, 5th and 6th) methods. The number of proflow data is 8252 and the number of squeegee data is 9447.

It was observed that good frequency is 99.9% and error frequency is 0.1% when the squeegee method is used in the process. However, the proflow value is very close to squeegee results. The good frequency is 99.8% and the error frequency is 0.2% (Table 17).

Table 17. Distributions of error and good data according to method type for C137

Method Type	Good/Error	Frequency	Percent	Valid Percent
Proflow	Good	8238	99.8	99.8
	Error	14	0.2	0.2
Squeegee	Good	9436	99.9	99.9
	Error	11	0.1	0.1

The description statistic is shown that solder paste variation is deposited more by using squeegee method than usage of squeegee. The amount of volume difference is 15% (Table 18).

Table 18. The descriptive statistic of proflow and squeegee for C137

Method Type	N	Minimum	Maximum	Mean	Standard Dev.
Proflow	8252	79.07	209.58	93.87	5.920
Squeegee	9447	3.70	141.94	108.40	5.660

According to process capability graph (Figure 36), the squeegee Cp value is bigger than proflow. Cp values for both two methods are respectively 3.942 and 4.123. The number of process capability is bigger than 1.33 in both proflow method and squeegee method.

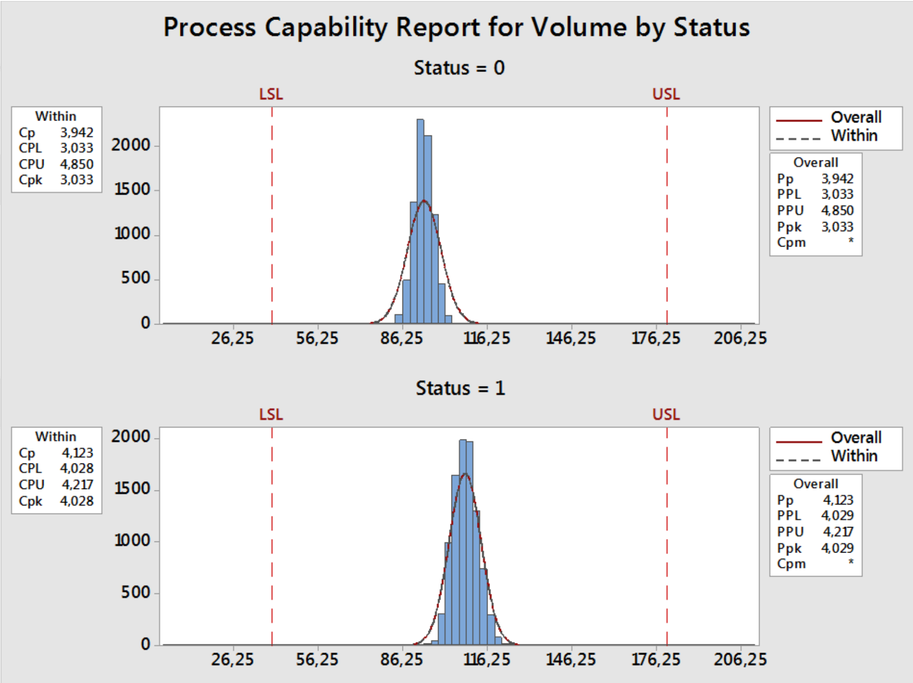

Figure 36. Process capability of Proflow and Squeegee for C137

4.3.4. Experiment 4

In the last experiment, the component which has one of the biggest pads and different shape was analysed in the process. The component called U66 has only one pad and the pad size is 0.4 mm x 0.4 mm (Figure 37). Component U66 has totally 96 pads to link with PCB.

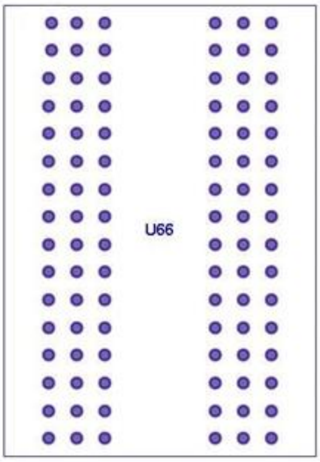

Figure 37. U66 type of component

The data on April 3rd, 4th, 5th and 6th were used for analysis of proflow and the data on April 20th, 21st, 25th, 26th, 27th were used for squeegee analysis. The number of proflow is 5404 and number of squeegee is 4460.

The descriptive statistic is shown that both of methods achieve to reach out optimal values. Their amounts of volume are both between 80% - 120% and more than 100%. It might be proved that squeegee deposits 4% more solder paste into pads (Table 19). This situation is considered as an advantage.

Table 19. The descriptive statistic of proflow and squeegee for U66

Method Type	N	Minimum	Maximum	Mean	Standard Dev.
Proflow	5404	80.96	126.60	104.44	6.142
Squeegee	4460	24.47	249.91	108.39	7.950

Figure 38 shows means and standard deviation of volume for U66, considering proflow printing and squeegee printing.

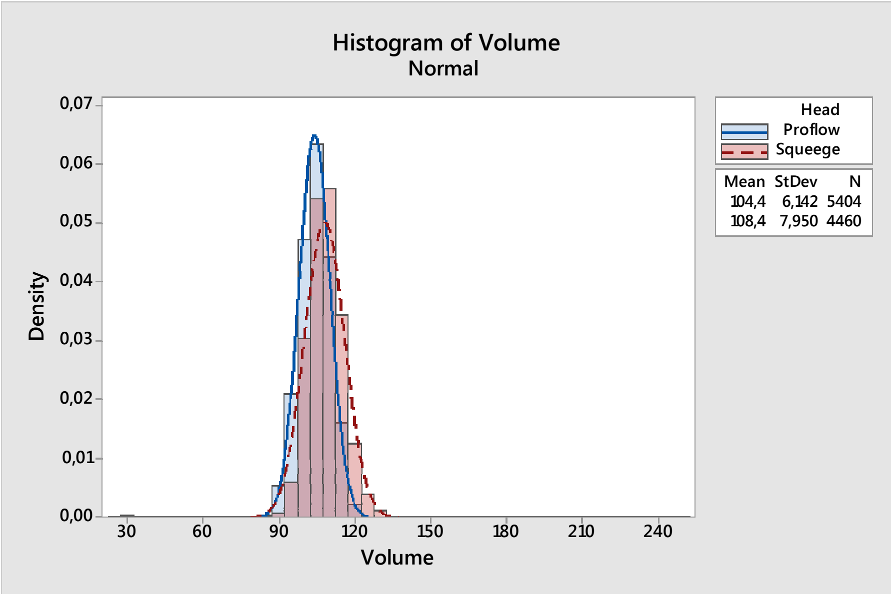

Figure 38. Standard variation of volume considering status for U66

4.3.5. Analyses of Result

In this study, it was evaluated whether there was a significant difference between the means in two unrelated groups by using independent samples t-test which evaluates the difference between the means of two independent or unrelated groups. With the independent sample-t test, it was evaluated whether the mean value of the volume defect for one group 'proflow' differs significantly from the mean value of the test variable for the second group 'squeegee'. Null and alternative hypotheses were set up for each experiment of the pad type (U29, C152, C137, U66).

In order to compare the significant different between statuses, significance level (alpha) was set up as 0.05 which allows the analysis to either reject or accept the alternative hypothesis.

Hypothesis for U29;

H_0: There was not a significant difference in volume defect of using U29 for ‘proflow’ and ‘squeegee’.

H_1: There was a significant difference in volume defect of using U29 for ‘proflow’ and ‘squeegee’.

Hypothesis for C152;

H_0: There was not a significant difference in volume defect of using C152 for ‘proflow’ and ‘squeegee’.

H_1: There was a significant difference in volume defect of using C152 for ‘proflow’ and ‘squeegee’.

Hypothesis for C137;

H_0: There was not a significant difference in volume defect of using C137 for 'proflow' and 'squeegee'.

H_1: There was a significant difference in volume defect of using C137 for 'proflow' and 'squeegee'.

Hypothesis for U66;

H_0: There was not a significant difference in volume defect of using U66 for 'proflow' and 'squeegee'.

H_1: There was a significant difference in volume defect of using U66 for 'proflow' and 'squeegee'.

In the difference between 'proflow' and 'squeegee' test, it was resulted in a Sig. (p) value that was less than significance level ($p < 0.05$). The null hypothesis was rejected, and the alternative hypothesis was accepted for each pad types shown in Table 20.

Table 20. The significance of volume according to status

Component Type	df	t	Sig.
U29	404812	-676.58	0.000
C137	176977	-166.85	0.000
C152	20244	-235.37	0.000
U66	9862	-27.87	0.000

There was a significant difference in volume defect of using pad U29 for 'proflow' (M=67.76, SD=7.969) and 'squeegee' (M=83.92, SD=7.106) conditions; t (404812) = -676.58, p=0.00.

There was a significant difference in volume defect of using pad C152 for 'proflow' (M=97.55, SD=6.968) and 'squeegee' (M=116.04, SD=3.34) conditions; t (176977) = -166.85, p=0.00.

There was a significant difference in volume defect of using pad C137 for 'proflow' (M=93.87, SD=5.92) and 'squeegee' (M=108.40, SD=5.66) conditions; t (20244) = -235.37, p=0.00.

There was a significant difference in volume defect of using pad U66 for 'proflow' (M=104.44, SD=6.142) and 'squeegee' (M=108.39, SD=7.95) conditions; t (9862) = -27.87, p=0.00.

4.4. Improve Phase

The improve phase is the fourth phase in DMAIC methodology. It was focused on solutions after analyse phase. According to (Sokovic 2005) the improve phase highlights developing thoughts to get rid of root causes of variation, testing and standardizing solutions. This section generally concentrates on improving and optimization of production or service quality.

In analyse phase, Proflow printing method which was used for long time in the process statistically was compared with Squeegee method. The comparison between current printing method and squeegee printing method was chosen as a way to improve the process instead of seeking new solutions. During this phase, those two data of different printing methods were analysed visually with tables and graphics by using statistical software. According to the result, it was proved that squeegee printing method might be more effective way to reduce defects. The reason of the thoughts bases on previous experience in the company that always accepted as an advantage that the amount of solder paste is more on the board. Therefore, the squeegee printing method which deposits more solder paste than proflow printing method has been accepted as a new method to be used in improve phase. Statistical experiments on four different pads as shown:

1. The analysis of the components named U29 which consists of smallest pads showed that the squeegee deposits 16% more solder paste into the pads.
2. According to analysis of named C152 component, its pads was filled 16% more solder paste into the apertures.
3. Amount of solder paste was found 15% more solder paste in the squeegee method when the deposition performance was compared between squeegees and proflow.
4. In the last observation of the last component named U66 showed that the results of the amount of solder paste were close to each other. However, it was slightly more in the squeegee method.

According to analysis interpretation, in next section, the process steps of the squeegee method will be shown in detail.

4.4.1. Operation of Squeegee Printing Method

Squeegee is one of the printing method in the SMT line. The squeegee module allows the setting and monitoring of squeegee height and pressure during the print stroke. The positioning of squeegee module is as follows:

Squeegee print-head mechanism including; Stepper Motors (2 positions), Leadscrews (2 positions), Spring Beam Assembly (optional), Home Sensor Micro-switches (2 positions), Squeegees, Squeegee Pressure Amplifier.

The print-head mechanism stepper motors drive he two squeegees independently down onto the stencil applying the pressure necessary to print. Its tools and the operation technically introduced as follows;

With the feedback pressure option fitted, the pressure being applied during the print is monitored, and if necessary, corrections to pressure are made as part of a closed loop process. The strain gauge bridge and pressure amplifier give a change in output voltage proportional to the pressure applied by squeegees. The home sensor, sited in the print-head mechanism, detect when the front and rear squeegee mounts are at the top of their travel (Figure 39).

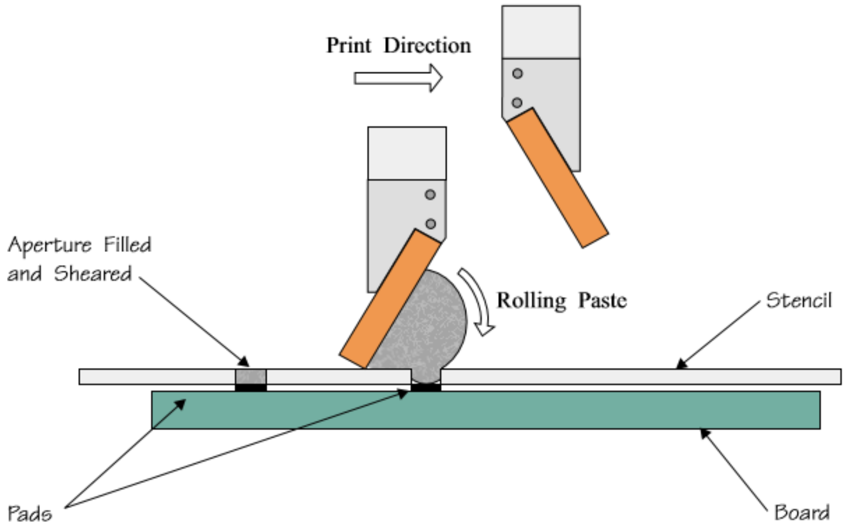

Figure 39. Squeegee printing method

A quantity of paste is placed on the stencil in front of the traveling squeegee. Due to the angle of the squeegee blade the paste has a tendency to move in rolling motion. This rolling motion plays very significant part in the distribution of paste and the final print quality. During the rolling action the paste is worked into and fills the apertures in the stencil, thereby showing the importance of the paste rolling action during printing.

With the stencil aperture already filled with paste and as the squeegee blade moves across the aperture, it effectively shears the paste cleanly at the surface of the stencil.

This action is dependent upon the edge of the squeegee blade being sharp and even, and that the correct amount of pressure is applied to squeegee. The squeegee acts on the solder paste to form a paste roll, and near the squeegee tip high pressures and shear rates are generated.

There are not differences among parameter adjustments when the printing method was switched from proflow to squeegee. The difference between proflow and squeegee is printing tool. Squeegee printing method technically has got two tools which are fitted to the print-head as the front squeegee and the rear squeegee. The front squeegee unit is fitted to the print-head mounting assembly last. For ease of access the rear squeegee unit is fitted to the print-head mounting assembly first (Figure 40).

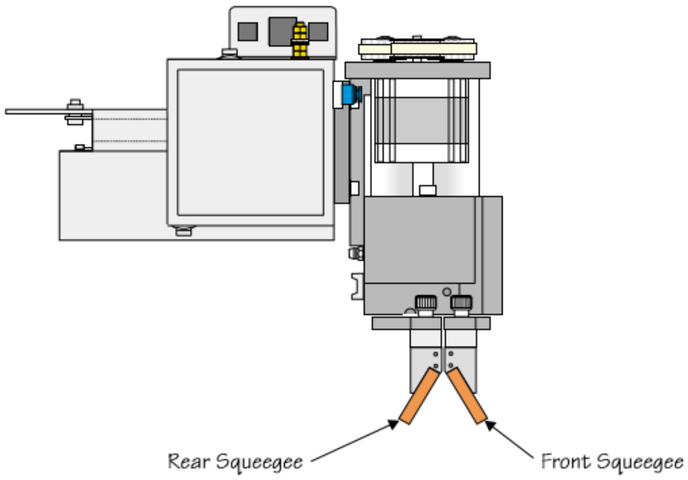

Figure 40. Squeegee Rear squeegee – Front squeegee

It is very important to understand what role the squeegee plays during the machine printing process. The squeegees play an extremely important role in producing a high quality printing process. It is therefore important to fit the correct squeegee for the type of work required, ensure the squeegee is prepared and maintained to enhance the print quality.

4.5. Control Phase

The main objective of the control phase is to ensure that the improvements are sustained, controlled ongoing operations and monitored properly. According to Jones (2014), the following steps are considered in this phase:

1. Run the new process
2. Monitor result carefully
3. Calculate performance statistic

4. Compare the actual result with the expected result

It was demonstrated that squeegee method was chosen in the printing process to eliminate the volume defect. Afterward, the squeegee method was technically introduced in improve phase.

In this phase, it will be proved that the performance of the new method and variation of volume error rates which are caused by using proflow and squeegee method. There are significant circumstances in the control phase to avoid the problems in the last phase.

The control phase was applied according to these particular steps:

- Implementing ongoing measurement
- Standardising the solutions
- Quantifying the improvement

In the first step, the sigma level was recalculated in the process that the squeegee was used. This result shows that the sigma level of process was increased by 0.2. This improvement percentage is an important value to raise the performance which aims to excellence production ideology.

Table 21. The new sigma level of process using squeegee method

	Volume	Position	Bridging	Height	Area	Total
Number of Pads Rejected	1566	38	116	2	3	1725
Total Number of Pads	13277760	13277760	13277760	13277760	13277760	13277760
DPMO	117.94	2.86	10.70	0.15	0.23	129.92
Sigma Level	5.2	Over 6	5.8	Over 6	Over 6	5.2

The volume DPMO changed from 243.04 to 117.94. This result showed that the squeegee method reduced more than half the volume amount of solder paste defects (compared to the previously used proflow method), ending up with an improved sigma level of 5.2 (Table 21).

The reason of using the same component in the analysis and control phases is to obtain a correct result in the process. In the future work, the analysis should be repeated for the same type of components analysed above (U29, C137, C152, and U66).

5. CONCLUSION

The conclusion presents the thesis generalization of this dissertation and some guidelines for future work. It was summarized that the study successfully achieved the proposed objectives and it has answered the performance improvement requirements of the Delphi Automotive in the work area.

In order to achieve a reducing defect rate and raising sigma level, DMAIC methodology was implemented in this study as a main Six Sigma methodology. Five phases (Define, Measure, Analyse, Improve, Control) were successfully applied step by step in accordance with the approach. This consideration was crucial to identify the critical root causes for the mentioned problem as well as to improve the process.

The defects of soldering paste printing were identified, classified into five types of defects, and its frequency was analysed. This work also used AHP, involving experienced workers, to assess the criticality of these types of defects, not assessing only its frequency, as it is reported in typical Six-Sigma projects. The criticality was defined as the product of the frequency. The volume defect was considered the most critical defect to be minimized.

The root cause of volume defects in the soldering paste printing process was decided by brainstorming, cause-and effect diagram and Pareto chart. The printing method “proflow” could be changed to an alternative method: “squeegee”.

The new printing method (squeegee) was compared with current method “proflow”. According to amount of volume, it was observed the reachability to the optimal value. The comparison indicated that the performance of the new method (Squeegee) reduced defects from 243 to 118 per million of opportunity by applying DMAIC methodology. Afterward, Squeegee printing method was introduced in the improve phase.

5.1 Thesis Generalization

The generalization of the thesis should answer following question: “Are the results (reduction in DPMO by changing proflow by squeegee method) applicable to other cases or other organizations?”

In this study and its context (equipment, materials, products and requirements) the squeegee method outperforms the proflow method. The case study used different components (PCBs) over several weeks.

5.2 Future Work

New case studies in different organizations can be done to apply the squeegee method in other assembly lines with different components to provide additional evidence to confirm these results. The detailed analysis of the involved costs could also be addressed.

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APPENDIX

Appendix-1 Sigma Conversion Table

Yield	Sigma	Defects per 1,000,000	Defects per 100,000	Defects per 10,000	Defects per 1,000	Defects per 100
99.99966%	6.0	3.4	0.34	0.034	0.0034	0.00034
99.9995%	5.9	5	0.5	0.05	0.005	0.0005
99.9992%	5.8	8	0.8	0.08	0.008	0.0008
99.9990%	5.7	10	1	0.1	0.01	0.001
99.9980%	5.6	20	2	0.2	0.02	0.002
99.9970%	5.5	30	3	0.3	0.03	0.003
99.9960%	5.4	40	4	0.4	0.04	0.004
99.9930%	5.3	70	7	0.7	0.07	0.007
99.9900%	5.2	100	10	1.0	0.1	0.01
99.9850%	5.1	150	15	1.5	0.15	0.015
99.9770%	5.0	230	23	2.3	0.23	0.023
99.9670%	4.9	330	33	3.3	0.33	0.033
99.9520%	4.8	480	48	4.8	0.48	0.048
99.9320%	4.7	680	68	6.8	0.68	0.068
99.9040%	4.6	960	96	9.6	0.96	0.096
99.8650%	4.5	1,350	135	13.5	1.35	0.135
99.8140%	4.4	1,860	186	18.6	1.86	0.186
99.7450%	4.3	2,550	255	25.5	2.55	0.255
99.6540%	4.2	3,460	346	34.6	3.46	0.346
99.5340%	4.1	4,660	466	46.6	4.66	0.466
99.3790%	4.0	6,210	621	62.1	6.21	0.621
99.1810%	3.9	8,190	819	81.9	8.19	0.819
98.930%	3.8	10,700	1,070	107	10.7	1.07
98.610%	3.7	13,900	1,390	139	13.9	1.39
98.220%	3.6	17,800	1,780	178	17.8	1.78
97.730%	3.5	22,700	2,270	227	22.7	2.27
97.130%	3.4	28,700	2,870	287	28.7	2.87
96.410%	3.3	35,900	3,590	359	35.9	3.59
95.540%	3.2	44,600	4,460	446	44.6	4.46
94.520%	3.1	54,800	5,480	548	54.8	5.48
93.320%	3.0	66,800	6,680	668	66.8	6.68
91.920%	2.9	80,800	8,080	808	80.8	8.08
90.320%	2.8	96,800	9,680	968	96.8	9.68
88.50%	2.7	115,000	11,500	1,150	115	11.5
86.50%	2.6	135,000	13,500	1,350	135	13.5
84.20%	2.5	158,000	15,800	1,580	158	15.8
81.60%	2.4	184,000	18,400	1,840	184	18.4
78.80%	2.3	212,000	21,200	2,120	212	21.2
75.80%	2.2	242,000	24,200	2,420	242	24.2
72.60%	2.1	274,000	27,400	2,740	274	27.4
69.20%	2.0	308,000	30,800	3,080	308	30.8
65.60%	1.9	344,000	34,400	3,440	344	34.4
61.80%	1.8	382,000	38,200	3,820	382	38.2
58.00%	1.7	420,000	42,000	4,200	420	42
54.00%	1.6	460,000	46,000	4,600	460	46
50%	1.5	500,000	50,000	5,000	500	50
46%	1.4	540,000	54,000	5,400	540	54
43%	1.3	570,000	57,000	5,700	570	57

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