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ScienceDirect

Procedia Manufacturing 38 (2019) 1592–1599

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

29th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2019), June 24-28, 2019, Limerick, Ireland.

Six Sigma application for quality improvement of the pin insertion process

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Abstract

Six Sigma is a systematic and organized, client-oriented approach that aims to improve the performance and quality of processes, products and services using statistical techniques. This paper presents a case study performed in an automotive company that intends to reduce the defective units produced by an automatic process, the process of single pin insertion, using the DMAIC (Define, Measure, Analyze, Improve, Control) method that is a structured way to carried out Six Sigma projects. In this process, excessive pin insertion force on Printed Circuit Boards (PCBs) entailed high rejection costs and line stop times that affected the supply of the final assembly lines. Therefore, the application of Six Sigma had the purpose to increase the quantity of products produced well at the first time and to reduce the quality costs associated to the process. To this end, the problem was defined, measured and analyzed starting from the machine and the two products with the highest number of rejections. An exhaustive analysis to determine the root cause allowed concluding that the excessive force is generated by the interaction of three factors: the PCBs physical characteristics, the pins contact zone and the wear of the machine components. A set of improvements focused on these factors raised the quality levels of the process, making it more stable and with less variability, by reducing the insertion forces to values closer to the nominal value. Methods for keeping the process under control were also defined and implemented. The use of some quality tools and the Six Sigma methodology proved to be extremely positive since this has led to significant improvements in the quality of the pin insertion process.

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Peer-review under responsibility of the scientific committee of the Flexible Automation and Intelligent Manufacturing 2019 (FAIM 2019)
10.1016/j.promfg.2020.01.126

Keywords: Six Sigma; DMAIC; Pin Insertion.

1. Introduction

Due to the constant change in customer needs, new markets, innovation and other external factors, pressure has been placed on organizations to continually improve the quality levels of their current processes and develop new processes to meet market trends. For that purpose, robust methodologies of quality management can be used, such as Six Sigma [1] [2]. According to Linderman et al. [3], Six Sigma can be seen as a systematic and organized, customer-oriented methodology that aims to improve the performance and quality of processes, products and services using statistical techniques and the scientific method to analyze data and make decisions. The application of Six Sigma in repetitive processes has brought significant gains to companies.

This paper describes a project carried out at a company of the automotive industry, whose objective was to reduce the number of defective units in the process of pins insertion in printed circuit boards (PCBs) that are part of Electronic Stability Program (ESP) sensors, using the Six Sigma methodology. It has been found that the excessive force in the insertion of pins, when present in the production process, results in high rejection costs and line stop times that compromise the supply of the final assembly lines. With the project, it was intended to reduce the quality costs in this process and increase the quantity of products produced well at the first time, so as not to compromise the supply of the final assembly lines. In this paper we show the significant advantages obtained for the pin insertion process by applying the DMAIC structured approach of the Six Sigma methodology, together with the Quality tools.

The paper was organized as follows. Section 2 presents a literature review on Six Sigma. Section 3 describes the pin insertion process. In section 4, the project is reported following the five steps of the DMAIC methodology. The last section presents conclusions on the methodology implementation in the process of pins insertion.

2. Literature review

The Six Sigma concept emerged in the 1980s on the initiative of Motorola Inc. in the USA. Due to competition from the Japanese electronics manufacturing industries, Motorola was forced to reduce defect levels while simultaneously reducing costs and increasing productivity and customer satisfaction [4] [5]. Afterwards, other companies implemented this methodology, obtaining exceptional economic savings [6].

The Six Sigma methodology can be considered from a statistical perspective and an economic perspective [7]. According to the statistical perspective, Six Sigma is viewed from a more technical point of view [5]. The Greek letter "σ", referred to as sigma, is used by statisticians to represent the standard deviation of a set of data [8] [9]. In the context of Six Sigma, the term sigma portrays the intrinsic variability of production processes, products and services in relation to a nominal value, the value of which is inversely proportional to their quality [5] [10]. Thus, the methodology focuses on reducing the variability of the processes so that the products (outputs) are as close as possible to their target value and efficient processes are obtained without waste, generating added value for customers [10] [11]. The objective is to reduce the number of defects produced through the reduction of variation to values close to 6 sigma (between specification limits), since the probability of obtaining values outside the Lower Specification Limit (LSL) and Upper Specification Limit (USL) will decrease. Therefore, considering a process centered on the nominal value, that follows a Normal distribution, 6σ reflects, in the short term, 0.002 defectives per million (PPM) or a percentage of conforming products of 99.9999998% [1]. In the long term, the process mean tends to vary $\pm 1{,}5\sigma$, with the USL or the LSL being $4{,}5\sigma$ from the process mean resulting in 3,4 PPM and 99,99966% of products meeting specifications [1] [10].

On the other hand, from an economic perspective, Six Sigma is recognized as a strategy that can be used by organizations, with the objective of increasing the profitability of the business, by focusing on improving the effectiveness and efficiency of internal and external operations, in order to meet customer needs [12].

To improve processes, products and services, organizations should, according to the context, adopt the most appropriate approach to apply the Six Sigma methodology. Thus, if the goal is to raise the performance of an existing process to a Six Sigma level, the organization must adopt the DMAIC approach, which consists of developing the following phases: Define, Measure, Analyze, Improve and Control [9]. The DMAIC approach is the most popular to support the Six Sigma methodology implementation [3]. Through the DMAIC method, it is possible to think of a problem sequentially, allowing the team to finish a phase and start the next phase smoothly, thus decomposing complex problems [14].

Preliminarily, the Six Sigma methodology was applied only in the productive sector, but once the benefit of its application in terms of performance improvement and cost reduction was found, it quickly expanded to different functional areas such as administrative, marketing, engineering and purchasing [6]. For instance, Ferreira and Lopes [15] obtained significant gains, in its application to the scrap request process of electronic controllers. The automotive sector is one of the areas where efforts have been made to apply Six Sigma because it is a highly competitive market where high standards of quality and safety are required [16]. The reduction of defects and associated costs, the reduction on process variability and the improvement on quality levels that Six Sigma enables, reflect the power of this initiative not only to address the current and future challenges of the automotive industry but also in the quest for organizational excellence [17] [18].

In 2007, Kumar et al. [19] applied the DMAIC approach of the Six Sigma methodology in an automotive manufacturing industry in order to identify and control the parameters that cause defects in the casting process. In the study, in combination with DMAIC, they applied tools and techniques such as: i) Pareto diagram; ii) Measurement System Analysis (MSA), reproducibility and repeatability study (Gauge R&R); iii) Cause and Effect Diagram; iv) Cause and Effect Matrix; v) Regression analysis; vi) Design of Experiments (DoE); and (vii) Control charts. The results of the study demonstrated the effectiveness of the Six Sigma methodology, which allowed increasing the process capacity from 0.49 to 1.28 and reducing the defects per unit (DPU) from 0.194 to 0.029, through the variability reduction of the porosity of the silica used in the casting process. The improvement of the process performance resulted in a saving in the quality costs of the casting process of about 213 728 € after one year of project completion, exceeding the reduction of 94 350 € estimated during the project.

Even more recently, Kaushik et al. [20] applied the same approach in a Small and Medium-sized Enterprise (SME) producing vehicle components in India with the aim of reducing rejection of a component, referred to as bush, which is an important component of a cycle-chain. This reduction was made possible by the application of several techniques and tools of the DMAIC approach such as: i) SIPOC diagram; ii) MSA, reproducibility and repeatability (Gauge R & R); iii) process capability study; iv) Cause and Effect diagram; v) two sample t-test; vi) DoE; (vii) Control charts. This Project allowed reducing the defects by 80 213.05 PPM and raising the sigma level of the process from 1.40σ to 5.46σ, by the variability reduction of the bush diameter in the chain manufacturing process, and led to a monetary saving of € 5 859 per year.

3. The pin insertion process

The pin insertion process (PIP) under study is intended to ensure an electrical connection to the PCBs. The input of this process consists of a panel, referred as nutzen, which contains several PCBs before getting cut in the Milling Process. The PCBs have several holes, where pins can be inserted, which can range from a minimum of 4 to 8 depending on the connector to be inserted.

This process begins with the supply made by the PCB feeder, a machine commonly called loader, of printed nutzens that come from the Surface Mounted Devices (SMDs) in specific containers for this purpose. The conveyor moves the nutzens to the pin insertion machine, and the thickness measurement is carried out at the entrance in an area suitable for the purpose. In the insertion machine, the nutzen remains fixed through the index pins present on the work table. According to the insertion program, the pins are inserted into the PCBs with a height previously established, through an existing bolt in the insertion finger (Fig. 1) and the insertion force is measured through a load cell present in the machine. Then, the insertion inspection is performed using an Automatic Optical Inspection (AOI), which verifies the presence of all the pins, and whether its deviation or inclination conforms to the specification. Since the PIP is a no repair process and false rejection is high, there is an operator to validate the indication of rejection made by the AOI. Finally, after inspection, the nutzens are directed to the unloader, which places them back automatically into containers.

The PIP provides a weld less electrical connection between the inserted pins and the PCB insertion hole. It is through the pin contact zone (press-fit zone) with the plated through hole (PTH) that the electrical connection is guaranteed. In order not to damage the PTH during insertion of pins, they must be inserted as close as possible to the axis of the holes, i.e., slightly inclined and all their geometry (edges, corners or stamping points) that comes into contact with PTH during or after insertion should be rounded (no sharp edges or surface roughness).

Prior to the start of production, a validation is carried out under a microscope to evaluate, according to the specification, the height and inclination of the pins. This evaluation is made each: start of production, change of shift, change of pin roller and intervention in the machine. Currently, only two pins are analyzed in each PCB and the pin height measurement is performed through two focus points.

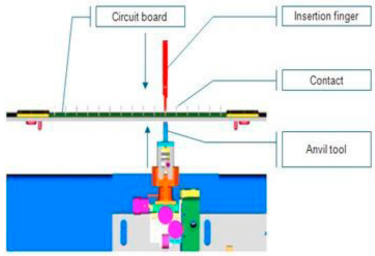

Fig. 1. Pin insertion scheme.

4. The Six Sigma project

The Six Sigma project is presented next following the DMAIC steps.

4.1. Define

In this first phase, the project team was defined. The team was composed by a team leader, a Black Belt from the engineering department, the process owner, the process factory expert, the process maintenance expert, two quality responsible and a sponsor. During the project, two supply quality engineers, responsible for the quality of PCBs and pins, were also involved.

After selecting the project team, the following steps were carried out:

- Formalization of the Six Sigma project, where the name of the project, the time period for data to be analyzed and the schedule of the work to be performed were defined. The expectations of the project were exposed, especially with regard to the benefits to the company. A project charter was issued containing this information.
- Process characterization. Both the inputs that can affect the performance of the pin insertion and the outputs to be improved were identified using a SIPOC diagram. This tool allows focusing on the factors that cause variation in the process.
- Definition of the project metrics. The defect was considered to be an insertion force above the upper specification limit (180N) that results in copper rupture and loss of electrical functions. Some others metrics were used such as the number of scrap PCBs and associated scrap costs.
- Sigma level calculation. The initial sigma level was calculated based on data from a time interval of eight months. The initial value was 4,22σ. For the project to be considered successful, the goal to be achieved was to reduce the DPMO (defects per million opportunities) by at least 50%, which is equivalent to a sigma level of 4.44.

4.2. Measure

The values of the insertion force are measured from a load cell that is coupled to the Anvil (Fig. 1). The load cell requires an annual calibration, since, over time, there is a significant variation due to fatigue or mechanical stresses. As such, to ensure the reliability of the measured values the team decided to send the load cell for calibration.

In order to determine the current state of the pin insertion process, data were collected in the company information system. The analysis covered data of 8 month for the two pin insertion machines of the process. A first analysis of the mensal rejected pins reveals an increase over the 8 month. Through the Pareto diagram shown in Fig. 2 that includes the rejection of PCBs of the two pin machines, it was found that there are two products that are more critical than the others, product 301368 and product 300374.

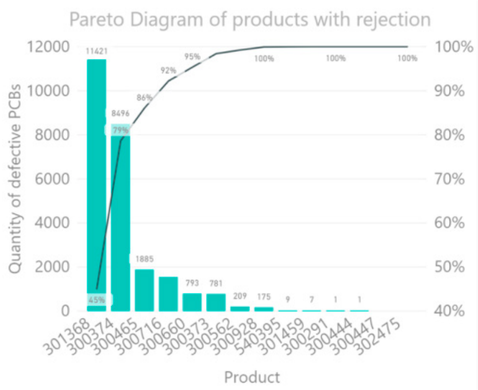

Fig. 2. Pareto diagram of the defective pins for each manufactured products.

Therefore, these products have been defined as priorities in improving the process, as they will solve a large part of the rejection. It was also decided to focus on the machine with the associated biggest number of rejections.

4.3. Analyze

As a starting point, a query was made in the company information system, in order to know which companies supply the PCBs of these two products. The product 300374 is wholly supplied by supplier A, whereas, product 301368 has a supply quota of 80% of supplier A and 20% of supplier B. Thus, although with different supply quotas, the PCBs of these two products are supplied mostly by the same supplier, and this was considered as an indicator to be taken into account for the problem under study.

On the other hand, an analysis was made to identify the impact of insertion forces above the upper limit. This analysis involved the examination of sectional sections through an optical microscope with a magnification of 500x. The sectional sections were longitudinal and transverse. The longitudinal cuts are performed in a vertical plane, aiming to examine the remaining copper thickness (after insertion of a pin), jet effect (entraining effect of PCB copper layers upon pin insertion), whitening (impact or stress caused by the pin embedded in the fiberglass of the PCB) and pin protrusion (distance between the lower tip of the pin and the base of the PCB). The transverse cuts are made in a horizontal plane in the contact zone of the pin, aiming to examine the copper thickness and whitening. The examination of the sectional sections shows that, for insertion forces above the upper limit, copper often breaks compromising the minimum thickness of copper in the hole and having also an effect in the fiberglass.

After an open and intense team discussion about the potential causes of the problem under study, a cause and effect diagram was developed. In view of the various possible causes indicated in the diagram, priority was assigned taking into account the experience of stakeholders and the knowledge transmitted between companies of the group. Therefore, the possible causes were classified as being "High" (E), "Medium" (M) or “low”. Those considered to be of "high" priority were analyzed, leading to several analyses:

- Analysis of the maintenance plan and the status of the insertion head and cutting tools.
- Copper analysis of the PCBs. Through the sectional cuts made to defective PCBS, the minimum, maximum and average values of the copper deposited in each hole were determined. A graphical analysis of the values was also performed;
- Analysis of PCB hole diameters. The mean and standard deviation of the minimum diameter was determined for sectioned PCBs.

- Analysis of hole geometry. An analysis was made of the ovality of the holes, given by the ratio between the maximum diameter and the minimum diameter.
- Dimensional analysis of the pins. The team decided to analyze 23 pins in each of three boxes associated with times of high rejection and 69 (3x23) pins of a box identified as "test" that was collected at a time when the rejection decreased. The diameter of the contact zone and the height of the “pin shoulder” were analyzed.
- Analysis of the pins composition and geometry. Regarding the composition of the pins, the supplier was asked to submit a history. Sectional cuts were made to the pins with the objective of analyzing the geometry in the contact zone and measuring the gap that exists between the pin faces.

This DMAIC phase allows concluding that, the causes for the excessive force are mainly related to the interaction of the PCBs drilling and the contact zone of the pins, and the process maintenance also has its contribution. In the analysis of PCB drilling, it was found that the deposited copper thickness was on average very close to the specification upper limit, and therefore the diameter decreased to a mean value of 1.030 mm which implies difficulties in the pins insertion. Also with regard to drilling, the presence of burrs or irregularities in the holes, caused by the condition of the supplier’ drill, becomes an obstruction to the pin at the insertion. Regarding the pin, with the completed analyzes, it was detected that the state of the joint and the contact zone also contribute negatively to the problem. The mechanical concept of the pin requires the joint and the contact area to be "polished" so that there are no obstructions at the time of insertion. It is essential to respect the state and spacing of the joint so that the pin contracts sufficiently, whereas the state of the contact zone will dictate the occurrence of more or less friction in the insertion. The preventive maintenance of the insertion head is performed annually and preventive maintenance of the cutting tools is carried out according to the degradation presented when checked, i.e., without any defined replacement periodicity, reason why its replacement is often forgotten. The filings that result from the cutting of the pins accumulate inside the machine due to the rupture of the suction pipe, reached by erosion caused by the filings.

4.4. Improve

In the Improve phase, several measures were defined based on the results of the previous analysis:

- Definition of the periodicity of preventive maintenance to the cutter, cutter blade and feeding finger. For the definition of the periodicity, the tools wear was analyzed after a million inserted pins and compared to new tools.
- Change in the periodicity of preventive maintenance of the insertion head, which will be carried out taking into account the number of pins inserted. Since it is a maintenance that involves the stopping of the line for at least 8 hours and high components cost, the number of cycles will be defined taking into account the wear of the components 6 months after the last annual maintenance performed. If the components do not show considerable wear at the end of 6 months, another check will be carried out with a time interval to be defined, and the data of the number of inserted pins will be collected, thus defining the optimal maintenance period, in an iterative way.
- Changing the material of the fillings suction pipe to avoid rupture and accumulation of dirt inside the machine.
- Request to the PCB supplier an average copper deposition in the holes near the nominal value (42.5 μm), in order to obtain diameters close to the nominal value (1,070 mm) since, as detected in the analysis phase, the average copper deposited in each hole of the PCBs was close to the upper specification limit (55 μm).
- Implementation of a new pin with a different mechanical concept for future products and existing products. Concerning products 300374 and 301368, the respective costumers accepted the shift to the new pin. This new pin requires less insertion force and causes less variability in the height and pins inclination, which has been proven through tests and statistical analysis. The process capability was also studied.
- Changing the cross-insertion sequence of the several pins on a PCB, for linear sequence. Although this need was not identified during the analysis phase, it was considered relevant in order to reduce the wear of the machine table in the long term, as well as to reduce boards’ misalignment, thus contributing to the reduction of the friction and force of insertion due to a more centered insertion.
- Improvement of the adjustment of the machine for each start of production. The new validation method consists of the inspection of the height, from the tip to the surface of the PCB, and inclination of all the pins. This change allows producing with greater stability and, although all the pins are inspected instead of only two pins per PCB,

the inspection time has decreased by an average of about one minute since the previous measurement process was more time-consuming.
- Preparation of drilling inspection programs for all products in order to monitor the diameters of PCBs and alert the supplier when they reach the reaction limit of 1,040 mm in diameter, a value defined as critical for the process by the performed analysis. Although the supplier complies with the specification, there are drill diameter values that become problematic for the process due to the amount of copper deposited.
- Development of an application for registration of batches of PCBs and pins. Although internally in the company this registration is already carried out for traceability reasons, several PCBs and several pin rolls of different batches are frequently present in the line so that there are no stops due to lack of material. Through this application it will be possible to consult what material was used in each production, with the added benefit of changeover time counting. In this way there will be a history of the raw material used, making it easier to track supply problems that may arise.

4.5. Control

During the implementation of the improvements in the process, the team monitored daily production on the line, giving support to what was required by operators, in particular with regard to validation under the microscope. This on-site monitoring also sought to ascertain the occurrence of problems or the need for adjustments after the implementation of each action. The annual maintenance at the head of insertion and replacement of the cutting tools, performed at week 18, resulted in a slight reduction of the rejection (Fig. 3), however, the inherent defects of the excessive force continued to exist.

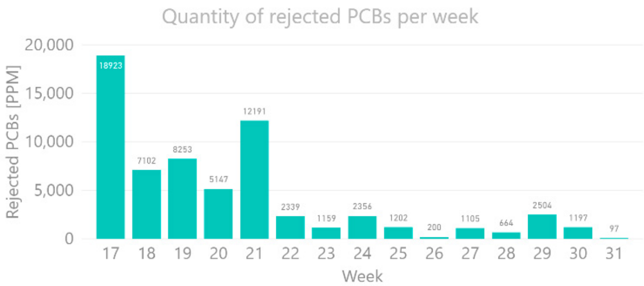

Fig. 3. Weekly values of the DPMOs in the period corresponding to the improvements implementation

The adjustment of the amount of copper deposited in the drilling to average values close to the nominal value (made by the supplier) was verified in both products between week 22 and 24 and was one of the essential measures to reduce the problem. The new pin was integrated into the product 300374 three months later, having inserted 5280 pins without defects. The new pin confers a reduced variability, which was verified through a statistical analysis. In addition, the average force that this pin has is lower and closer to the nominal value compared to the old one.

The implemented initiatives allowed reducing insertion forces to values close to nominal in the product 300374 and in the product 301368 and, consequently, the defects to a value of 312 PPM, increasing the sigma level to 4.92. In this way, the objectives proposed in the project definition phase were exceeded. It was estimated, considering the initial rejection and current rejection of the studied products that, in the next five months, the company will save about € 9.529 with the product 300374 and € 112.531 with the product 301368, due to this work.

5. Conclusion

This paper describes the accomplishment of a six sigma project that consisted of reducing the number of defective units produced by the pin insertion process in an automotive industry through the application of Six Sigma methodology, in order to reduce the inherent quality costs and not compromise the supply of final assembly lines.

An exhaustive analysis was performed to determine the root cause, and it was concluded that it is the interaction of three factors that gives rise to the excessive insertion force: the PCBs physical characteristics, the pins contact zone and the wear of machine components. The set of improvements, implemented with focus on the three mentioned factors, raised the quality levels of the process, making it more stable and with less variability by reducing the insertion forces to values close to the nominal. The effectiveness evaluation of the improvement actions revealed the overcoming of the objectives proposed in the project definition phase, through the reduction in the number of defective units from 3231 PPM to 312 PPM and the increase in the sigma level from 4.22 to 4.92, which results in significant savings for the company, estimated at around 122 thousand Euros.

The DMAIC structured approach served as the basis for problems solving, that coupled with quality tools such as Pareto diagram, control charts, cause and effect diagram, flowcharts and some six sigma tools proved to be gainful, as it resulted in significant improvements in product quality, allowed the reduction of costs and encouraged the start of other projects using a similar approach. However, it was noticed that, in industrial environment, the "time" resource becomes an obstacle to using advanced tools.

Acknowledgements

This work has been supported by FCT – Fundação para a Ciência e Tecnologia within the Project Scope: UID/CEC/00319/2019.

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