QUALITY AND RELIABILITY ENGINEERING INTERNATIONAL
Qual. Reliab. Engng. Int. 2009; **25**:495–512
Published online 12 November 2008 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/qre.985

Case Study

Reducing the Quantity of Reworked Parts in a Robotic Arc Welding Process

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Today, the competitive environment of the knowledge age has been replaced with the competitive environment of the industrial age as the rules of the business world are changing completely. The focused issue is to reach to the knowledge as soon as possible, and to process and apply it rapidly. In this context, one of the important goals that the companies try to reach in order to achieve acceleration is the six sigma philosophy. Six sigma is a fundamental continuous improvement methodology aimed at reducing the variation and waste on processes by utilizing statistical methods and techniques efficiently. Global companies are making noteworthy profits by using this method in their processes. The six sigma methodology focuses on process excellence advantages for companies that apply it, to reach profit, to increase productivity and to have larger market share. In this paper, an application of six sigma methodology for reducing the quantity of rework parts for robotic arc welding process is given. The phases of six sigma and their results are indicated in detail. Furthermore, it is also shown how various techniques of six sigma methodology are applied to achieve financial benefits.

KEY WORDS: six sigma methodology; case study; robotic arc welding; quality; statistical tools

1. INTRODUCTION

Six sigma methodology was originally developed by Motorola in 1987 and it targeted a difficult goal of 3.4 parts per million (ppm) defects[1]. At that time, Motorola was facing the threat of Japanese competition in the electronics industry and needed to carry out drastic improvements in their quality levels[2]. In 1994, six sigma was introduced as a business initiative to 'produce high-level results, improve work processes, expand all employees' skills and change the culture'[3]. This introduction was followed by the well-revealed implementation of six sigma at General Electric beginning in 1995[4].

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After the first few successful implementations, even though six sigma began gaining momentum in industry, academics have conducted little research on this emerging phenomenon[5,6]. In spite of this being the case, leading organizations with a track record in quality have adopted six sigma and claimed that it has transformed their organizations[7]. For example, after 3M's Dental Division won the Baldrige Award[8] they applied six sigma to improve performance even further[9]. The financial routine of 3M since the six sigma implementation has been very remarkable[10]. Other organizations with a quality track record, such as Ford, Honeywell and American Express, have implemented six sigma as a means to further improve their company's performance[11].

The first rational and commonly known definition of six sigma is that it is a statistical tool. The lowercase Greek symbol 'sigma' is the metric or fundamental statistical concept that symbolizes a population's standard deviation and is a measure of variation or distribution about a mean[12]. Therefore, it measures the variability in a process.

Six sigma methodology uses defects per unit (DPU) as a measurement tool[13]. DPU is a good way to measure the quality of a process or product[14]. The defects usually link between the cost and the time. The sigma value further indicates the frequency at which failures occur; therefore, a higher sigma value means the less defect probability[15]. The defect can be defined as the dissatisfaction of the customer. Therefore, as sigma level increases, cost and cycle time decrease and at the same time customer satisfaction increases.

The six sigma method has two major perspectives. Its origin comes from statistics and statisticians[16]. The real focus of six sigma methodology is to reduce potential variability in processes and products by define measure analyze improve control (DMAIC) cycle[17,18]. Numerous books and articles provide the basic concepts and benefits of the six sigma method[19,20]. In this paper, the application of the DMAIC approach is applied step by step to reduce the number of reworked parts in a robotic arc welding process. The study begins with the selection of the project. After this step different phases of DMAIC approach, tools and techniques are shown and advantages and benefits are put forth for consideration[21–23].

In this paper the case study has the following sections: Section 2.1 indicates the define phase. Relevant current state data are given in Section 2.2 to identify the root cause. In Section 2.3, process capability is calculated and in Section 2.4, alternative solution proposals applied to improve the results according to the information from the previous sections are given. Results of improvement are given in Section 2.5. In Section 3, an overall evaluation of the results is given and the grade of improvement is emphasized. As a sequel to conclusions, Section 4 presents the lessons learned from the application of the six sigma methodology.

2. CASE STUDY

In this section the application of DMAIC approach to the quantity reduction of reworked parts in a robotic arc welding process is given. The first step of this approach is to set forth the definition of the problem.

2.1. Define phase

In order to define the problem, possible improvement targets emerging from customer requirements should be identified. Then, from the possible targets, the one that has more impact should be chosen. It should be noted that some outputs from this phase will be pinpointing at the selection of the project target. One can see the 'project tracking schedule' in Table I.

This case study, as explained before, deals with the reduction of the quantity of reworked parts in a robotic arc welding process. This process is established in the metal workshop of an automotive factory.

During the define phase, the following four steps are completed by the DMAIC approach:

1. Definition of the project goals and boundaries.
2. Definition of the defects.
3. Definition of the team schedule.
4. Estimation of the influence of the project.

DOI: 10.1002/qre

Table I. Project tracking schedule

Project phase	Planned target date	Closing date
Define	W24	W23
Measure	W28	W28
Analyze	W32	W32
Improve	W36	W36
Control	W40	W39

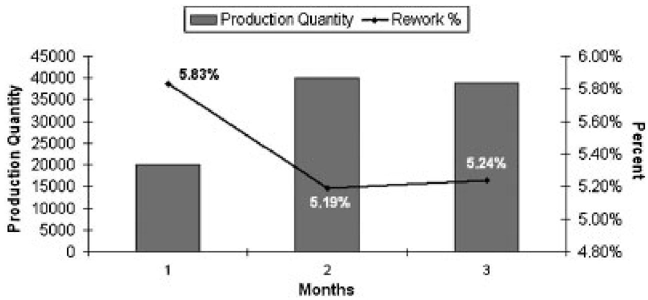

Figure 1. Reworked percentages for the last three months prior to case study

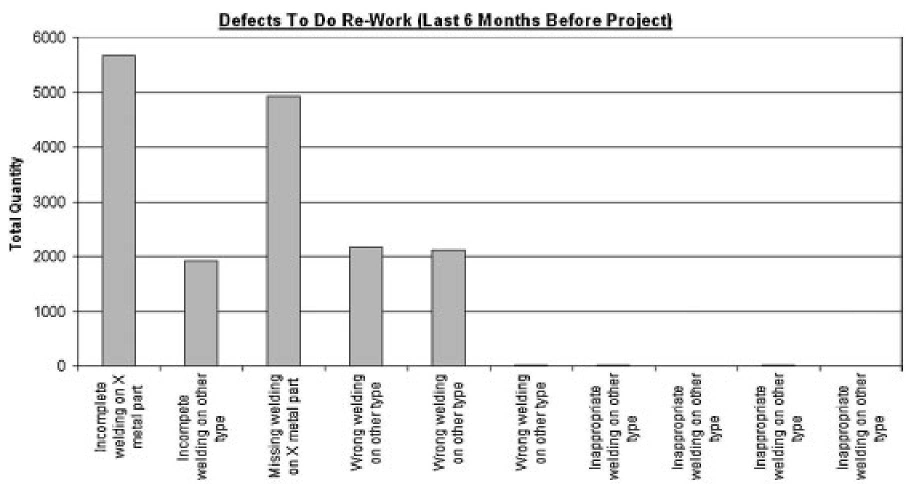

Figure 2. Defects requiring rework

In the selection of the project, related data of the production for the last three months were collected and analyzed. During this data collection period special attention was given to the problematic welding cell (see Figure 1). In order to decide on the problematic welding cell, total defects due to rework needs have been examined for all metal workshops. Figure 2 indicates the number of defects requiring rework six months prior to the project. It can be seen from this figure that two defects, namely ‘incomplete welding’ and ‘missing welding’, are the most common defects that lead to rework. Hence, it would be meaningful to select the welding cell that creates most of these defects and apply the six sigma methodology to this cell in order to have greater savings than the other cells. During this data collection phase, an average of 5% reworked parts rate was observed on the selected cell. Therefore, by analyzing each apparatus per daily

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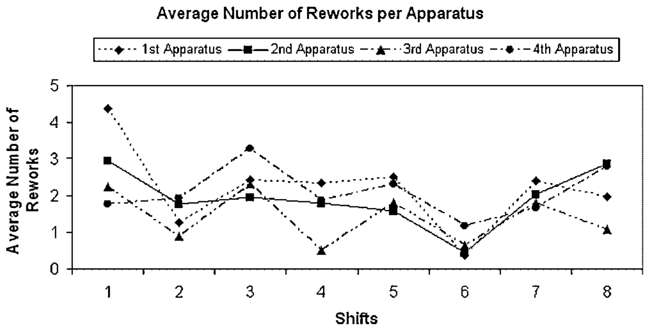

Figure 3. Average number of reworks per shift by apparatus

shift, the average number of reworked parts is obtained as shown in Figure 3. According to the results, 'six sigma statement of work' form is filled. The results are summarized as below.

- Problem target: To reduce the number of reworks
- Measurable factors that serve to improve target:
  - Y_{CX} = Number of reworks per Xth apparatus
  - For the rest of the paper X is the variable of 'front seat back frame robotic arc welding station'.
- Estimated project schedule:
  - Define phase: 1 week
  - Measure phase: 4 weeks
  - Analyze phase: 4 weeks
  - Improvement phase: 4 weeks
  - Control phase: 4 weeks
- Estimated improvement target: 40%

2.2. *Measure phase*

The aim of measure phase is to point out the actual reasons of the problems by constructing the current process and problems with the comprehension relying on reality. In order to get the process under control, first, the process flow as seen in Figure 4 is checked and a road map of process improvement is created. The road map is given in Figure 5.

Measurement system analysis (*MSA*): For the process at hand, the decision of whether the part will be reworked is given after visual inspection. No penetration analysis is done for the welding length exposed in welding points on the part. After the rework process, the quality operators perform the visual inspection over the completed frames (either reworked or not) and then continue through the approval process. As there is no measurement system tested by mathematical data, the system is observed by using the Minitab module 'Attribute Agreement Analysis'.

The method applied for this MSA study is as follows:

- Twenty completed frames are chosen for measurement and these frames are assigned numbers. In another list, not seen by appraisers, the frame quality of each number is written.
- It is required from each operator to look for the frames and give comments on each part. This process is repeated for 30 minute intervals.
- To pinpoint the variability arising from the operators, the method or the parts, the results are analyzed by Minitab.

The test is performed over 20 samples in a total of two rounds with two quality and three welding operators. After Minitab analysis, the following test results are obtained:

All appraisers vs standard: This assessment shows that all appraisers' assessments agree with the known standard of a ratio of 50%. The comparison of each appraiser is given in Figure 6. As it can be seen

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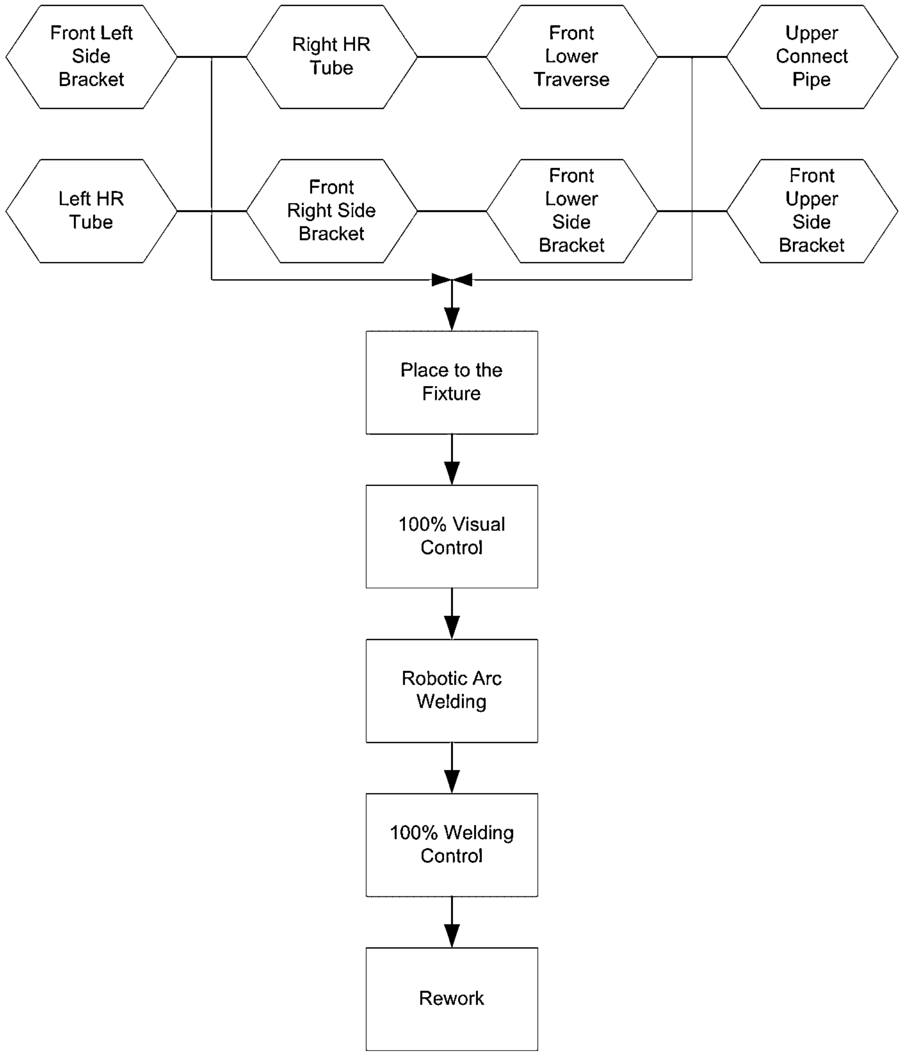

Figure 4. Process flow diagram

from the figure, the quality operators (first and second appraisers) need to be evaluated once more after training.

As indicated above the quality operators need a training program before reliable data collection for the project can be initiated. For this purpose, a detailed training program for these operators is prepared and conducted. Then, the same analyses as was accomplished before is repeated after this training period. It is observed that the capability grade of the quality operators' knowledge has increased compared with the previous results and the improvement reached to 80% level. Furthermore, there is some improvement in their consistency between each other. The final case can be seen in Figure 7.

Cause and effect analysis: After checking the process flow-chart and analyzing the measurement system, it is concluded that it is necessary to define the 'X' factors to be measured as a key step for the problem. These results will act as a road map for the analysis and improvement phases. The factors defined after brainstorming are summarized by the cause-and-effect diagram. The problem causes and their roots are given as follows:

1. Thin material (material).
2. Thick welding wire (material).

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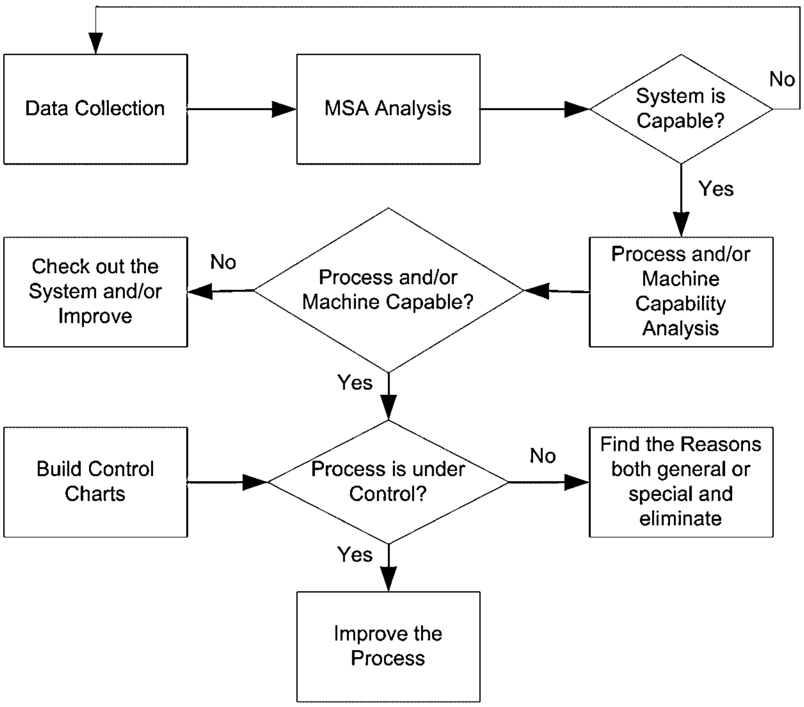

Figure 5. Process improvement road map

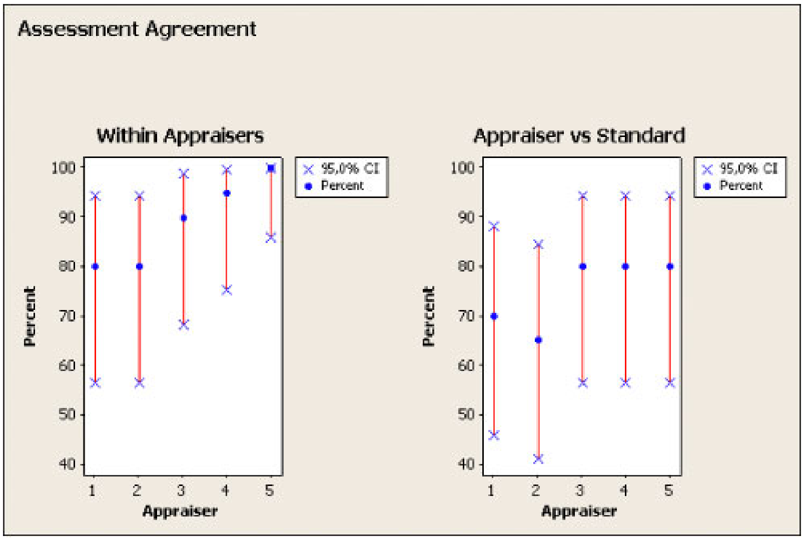

Figure 6. Assessment agreement

3. Seaming of hard welding tip with soft sheet iron part (material).
4. Failure in part geometry (material).
5. Wrong welding method (method).
6. Deviation in welding characteristics (method).

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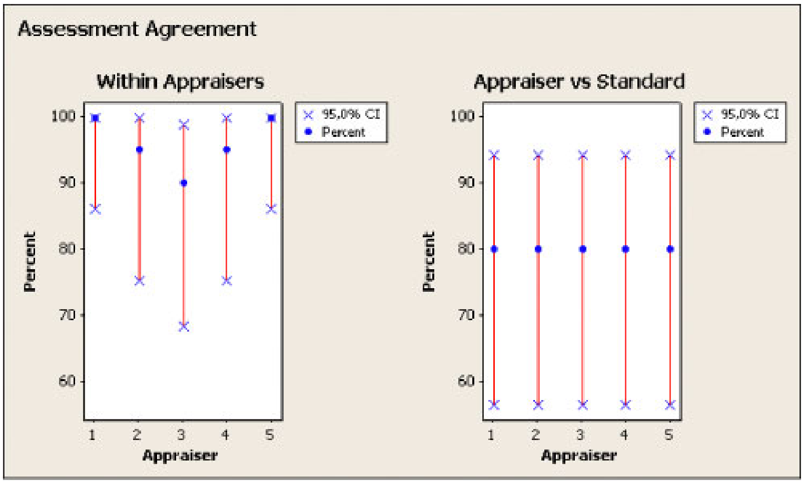

Figure 7. Assessment agreement after training

7. Unsuitable operation description sheets (work instruction) (method).
8. Change of the welding tip (method).
9. Air speed (environment).
10. Air current (environment).
11. Variation in electric current (environment).
12. Need of the revision of the parameter values (machines).
13. Unsuitable welding tip (machines).
14. Problems in robot settings (machines).
15. Not obeying the change frequency of welding nozzle (personnel).
16. Not controlling the position of the parts in the fixture at the beginning of the process (personnel).
17. Inappropriate positioning of the part in the fixture (personnel).
18. Not performing appropriate periodical maintenance (control of maintenance periods) (personnel).

The following steps are executed in order to make a sensitive and analytical decision among the potential problems listed above:

- A ten person 'professional team' is organized, which is formed of people from the metal production, engineering, quality, maintenance, technical reception departments.
- Each of the team members assigns a number from 1 to 10 to the potential root cause, with 10 being the biggest impact and 1 the smallest impact. The results are given in Table II.
- The total points of each potential root cause are calculated by summing the points in the relevant row.
- The potential root cause problems having the top 5 points are then selected.
- 'The expected effect point' is calculated by taking into account the 'applicability', 'time' and 'cost' issues of these top 5 potential root causes and a 'priority rank' is calculated. The corresponding precedence matrix can be seen in Table III. It should be noted that, in preparing the precedence matrix, the grading system used in the calculation is:
    - 0: Hard
    - 1: Easy
    - 2: Very easy

As a result, it is concluded that the most important potential root causes of the problem at hand are:

1. (12) Need of the revision of the parameter values: 78
2. (17) Inappropriate positioning of the part in the fixture: 69

Table II. The evaluation of potential root causes

	Impact										
Root causes	1	2	3	4	5	6	7	8	9	10	Total
1		4	3	6			7		3	1	24
2	6	3	5					5			19
3			6	8	5	3		6			28
4	7	2		7	3	4	4	7	8	3	45
5						7	6			5	18
6				5	9			8	7	9	38
7			8	4		1			2	7	22
8	1		1	3	2		2				9
9	1			3			2				6
10			2	1	1			3	1	4	12
11	8	1	7		4	2	1	9	9	10	51
12	10	7	10	10	7	6	8	10	10		78
13	5					5			5	7	22
14		8				9	9	2	4	8	40
15	2	9		2	2						15
16	3	5			6		3	1			18
17	9	10	4		10	10	10	4	6	6	69
18	4	6	9	9	8	8	5			2	51

Table III. The precedence matrix

Number of cause	Problem definition	Time (a)	Cost (b)	Applicability (c)	Expected effect (a+b+c)	Precedence
12	Need of the revision of the parameter values	1	1	1	3	2
17	Inappropriate positioning of the part in the fixture	1	0	1	2	3
18	Not performing the periodical maintenance (control of maintenance periods)	1	0	1	3	2
11	Variation in electric current	2	1	1	4	1
4-1	Failure in part geometry → Manual correction of the part geometry by operator at the beginning of the process	0	0	1	1	4
4-2	Failure in part geometry → Alteration of the part geometry by heaping in the delivery conditions	0	0	1	1	4

3. (18) Not performing appropriate periodical maintenance: 51
4. (11) Variation in electric current: 51
5. (4) Failure in part geometry: 45

Data collection plan: The following methods are applied for the data collection:

- The operator marks the reworked part using green, blue, red or black where each color defines a different fixture.
- The operator fills the relevant data 'operator name, shift and production quantity' in the relevant form.

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Table IV. Data processing form template

	Apparatuses				Parameter values (defined for each apparatus)		
Welding points	1.App.	2.App.	3.App.	4.App.	Welding voltage	Welding wire feed	Welding speed
	Rework quantities						
1					19.50	7.40	7.80
2					…	…	…
⋮					…	…	…
20					19.50	7.40	7.80

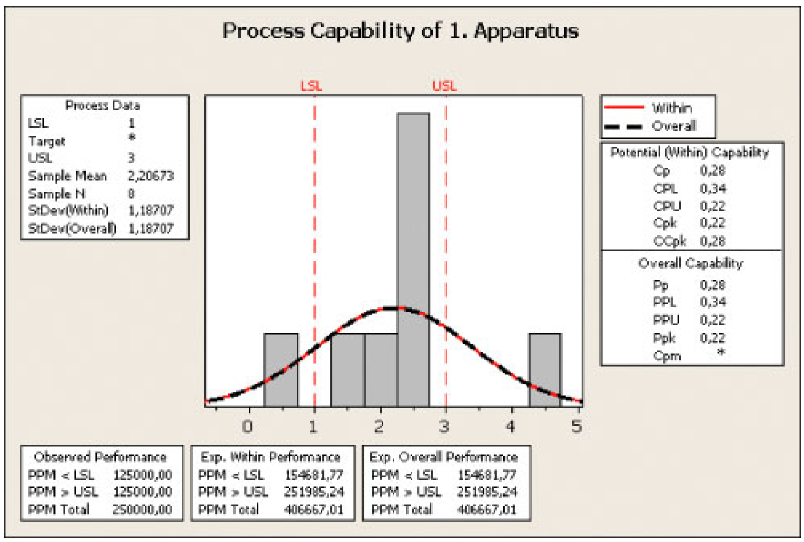

Figure 8. Process capability of the first apparatus

- The operator renews the forms at the end of each shift and hands than over to the next operator.
- Finally, the operator counts the number of each colored groups on the form and transfers these quantities into the 'the data processing form' as seen in Table IV.

In the subsequent sections of this application, the attainability of the improvement target by preventing variation in electric current, by performing a review of the parameter values and by controlling the appropriateness of the periodical maintenance will be explored.

2.3. Analysis phase

The aim of the analysis phase is to order the data, to classify and to prioritize it. The data that are collected from the beginning of the measurement phase are used in the analysis phase. The process capability values C_p and C_{pk} must be above 1.33 for this application[24]. After this process capability check, process must be under control. Otherwise the process must be checked, improved and taken under control once more. The process capabilities of the devices before improvement can be seen in Figures 8–11 and are summarized below:

For apparatus #1:

- $C_p = 0.28 < 1$. Process capability is insufficient. Process variation must be decreased.
- $C_{pk} = 0.22 < 1$. Process cannot reach specification limits. Process average value is away from the target value.

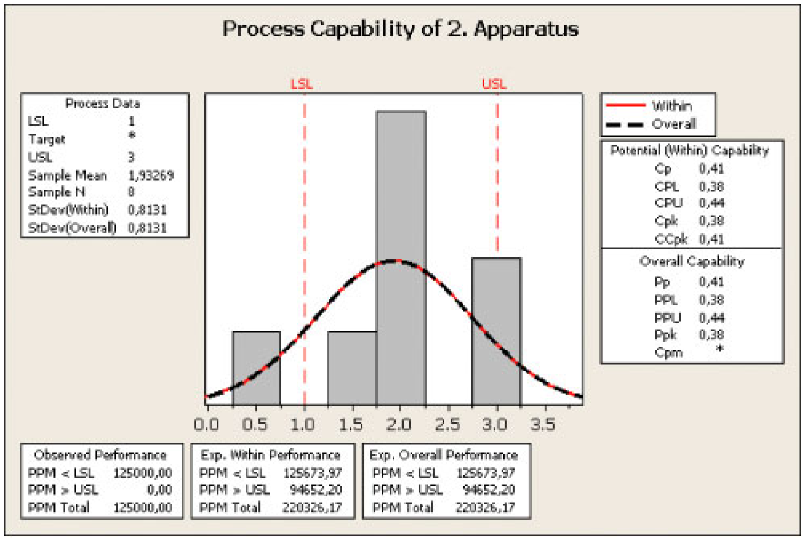

Figure 9. Process capability of the second apparatus

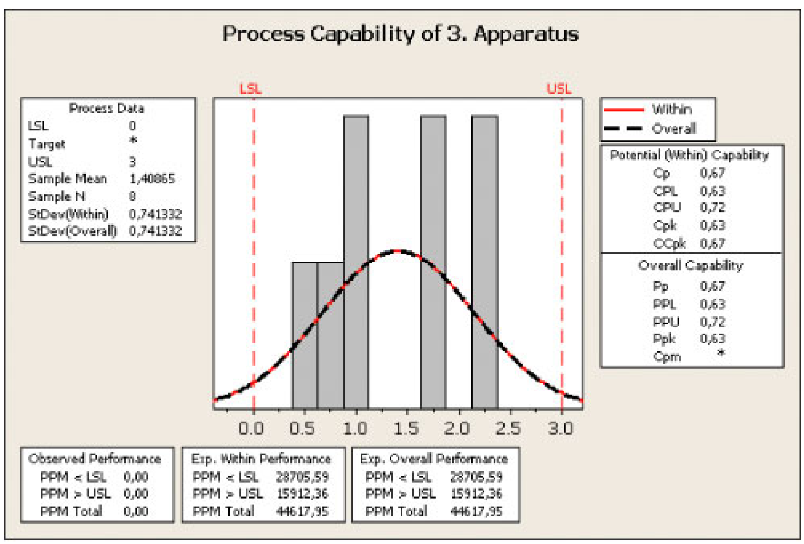

Figure 10. Process capability of the third apparatus

For apparatus #2:

- $C_p = 0.41 < 1$. Process capability is insufficient. Process variation must be decreased.
- $C_{pk} = 0.38 < 1$. Process cannot reach specification limits. Process average value is away from the target value.

For apparatus #3:

- $C_p = 0.67 < 1$. Process capability is insufficient. Process variation must be decreased.
- $C_{pk} = 0.63 < 1$. Process cannot reach specification limits. Process average value is away from the target value.

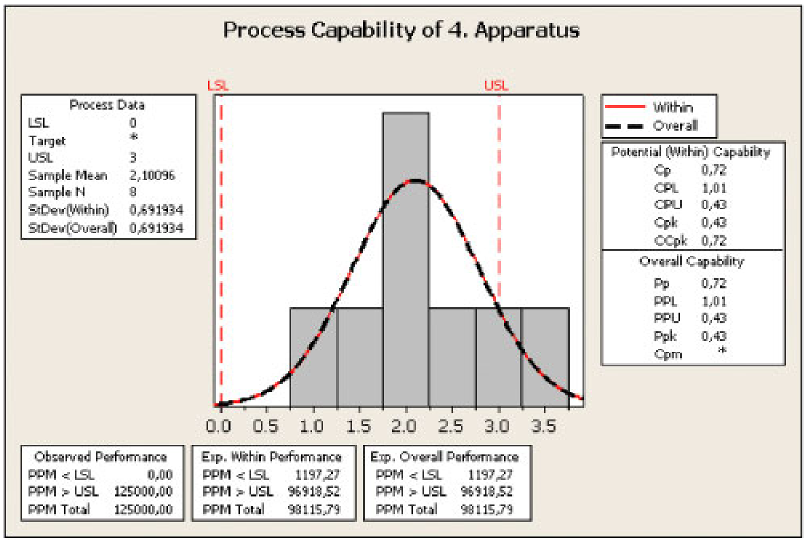

Figure 11. Process capability of the fourth apparatus

For apparatus #4:

- $C_p = 0.72 < 1$. Process capability is insufficient. Process variation must be decreased.
- $C_{pk} = 0.43 < 1$. Process cannot reach specification limits. Process average value is away from the target value.

2.4. *Improvement phase*

The aim of the improvement phase is to examine the reasons that appear during the analysis phase and to find solutions in order to eliminate them. As a result;

The team members list the following improvements to the root causes:

- As a solution of electric current variation problem, an electric ‘regulator’ is put into place and the reworked part data are collected after this improvement.
- At the same time, parameter values are looked over by a ‘robot adjustment group’. Some improvement values are suggested and in order to determine the validity of the values, frame parts that are welded according to these values have been given for penetration.
- New schedule proposals are prepared by the maintenance group.

These improvements are applied in two sets. After the first two improvements, the process capability is calculated and evaluated according to both cases. The results indicate that the process capability meets the specification limits. But it is necessary to decide whether these solution alternatives will be selected or not, after the hypothesis test. For the case study at hand, it will be suitable to compare the data of current and future states by the ‘2-sample t-test’. For this purpose, first the necessary $H0$ and $H1$ hypotheses are constructed and then the relevant probabilities are calculated:

$H0$: p(improvement proposal) $\geq p$ (normal – current state) – {reject}
$H1$: p(improvement proposal) $< p$ (normal – current state) – {approve}

- For apparatus #1: P-value $= 0.022 < 0.05$ approved
- For apparatus #2: P-value $= 0.010 < 0.05$ approved
- For apparatus #3: P-value $= 0.039 < 0.05$ approved
- For apparatus #4: P-value $= 0.002 < 0.05$ approved

The results indicate that it is convenient to use the new parameter values and the addition of regulator in all apparatuses.

DOI: 10.1002/qre

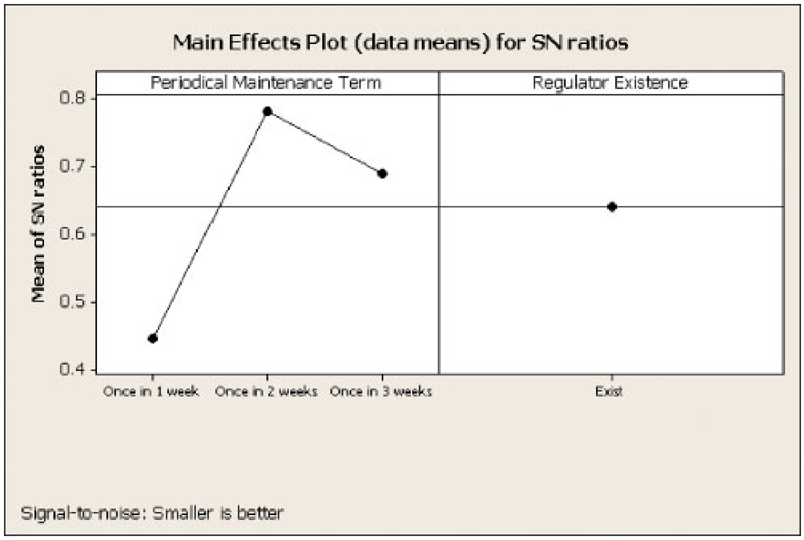

Figure 12. Effect comparison based on S/N ratio

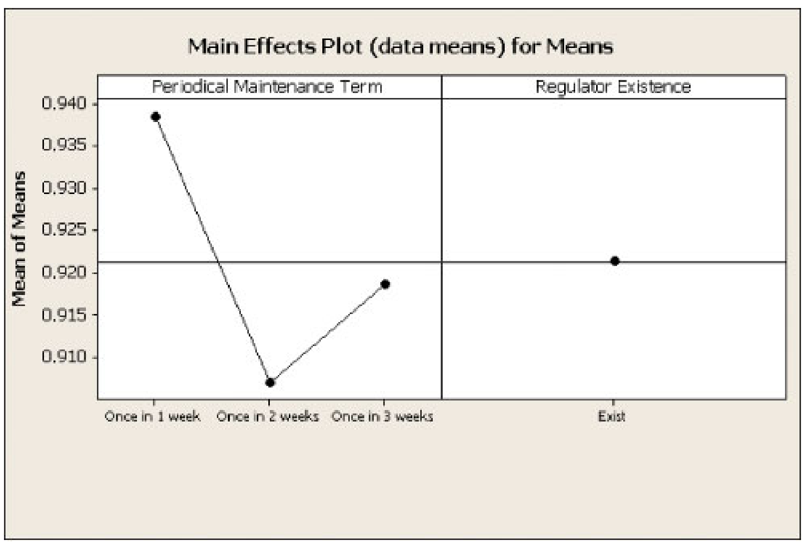

Figure 13. Effect comparison based on means

On the other hand a comparative analysis becomes inevitable regarding the control of the appropriateness of the periodical maintenance. As an alternative to the current 'once in a month' periodical maintenance, the following improved schedule proposals are evaluated:

- Once in 1 week
- Once in 2 weeks
- Once in 3 weeks

In order to decide on the most appropriate schedule, 'Taguchi analysis' in the Minitab program is applied for the collected reworked quantities. The objective is the maximization of signal-to-noise (S/N) ratios in all situations and the objective function is selected as 'smaller is better' (see Figures 12 and 13). The reason

DOI: 10.1002/qre

for selecting smaller is better for the objective is because one of the main goals of this case study is the minimization of the reworked parts.

According to Figures 12 and 13, ‘once in 2 weeks’ is the most suitable schedule compared with the others as it meets both the objective of maximization of an S/N ratio and the minimization of means. Additionally as explained above, it is needed to decide whether this schedule will be selected or not should depend on the hypothesis test. Once again 2-sample t-test is chosen with the same $H0$ and $H1$ hypotheses as above, and its results are summarized as follows:

- For apparatus #1: P-value $=0.023<0.05$ approved
- For apparatus #2: P-value $=0.012<0.05$ approved
- For apparatus #3: P-value $=0.032<0.05$ approved
- For apparatus #4: P-value $=0.002<0.05$ approved

These results indicate that it is appropriate to use the schedule ‘once in 2 weeks’.

As a result, after all these 3 improvement steps given above, i.e. addition of regulator, change of the parameter values and revision of periodical maintenance schedule, the improved status of the process capability is calculated and given through Figures 14–17. The results are summarized below:

For apparatus #1:

- $C_p = 1.68 > 1.33$. Process is capable.
- $C_{pk} = 1.65 > 1.33$. Process meets the specification limits.

For apparatus #2:

- $C_p = 1.49 > 1.33$. Process is capable.
- $C_{pk} = 1.46 > 1.33$. Process meets the specification limits.

For apparatus #3:

- $C_p = 2.06 > 1.33$. Process is capable.
- $C_{pk} = 1.49 > 1.33$. Process meets the specification limits.

For apparatus #4:

- $C_p = 1.54 > 1.33$. Process is capable.
- $C_{pk} = 1.40 > 1.33$. Process meets the specification limits.

It is concluded that all of the improvements are valid.

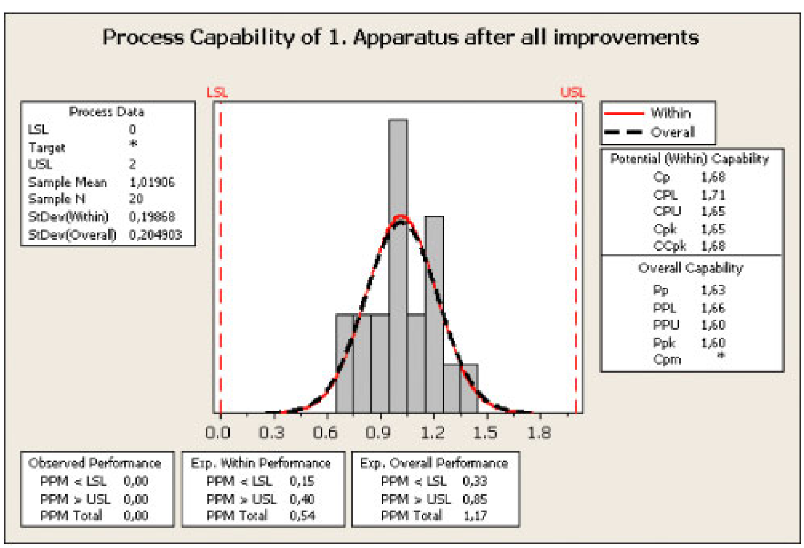

Figure 14. Process capability of the first apparatus after all improvements

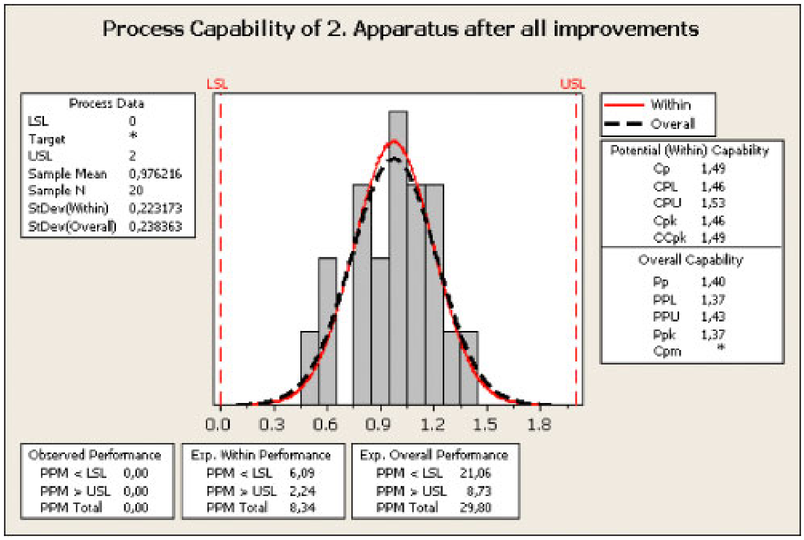

Figure 15. Process capability of the second apparatus after all improvements

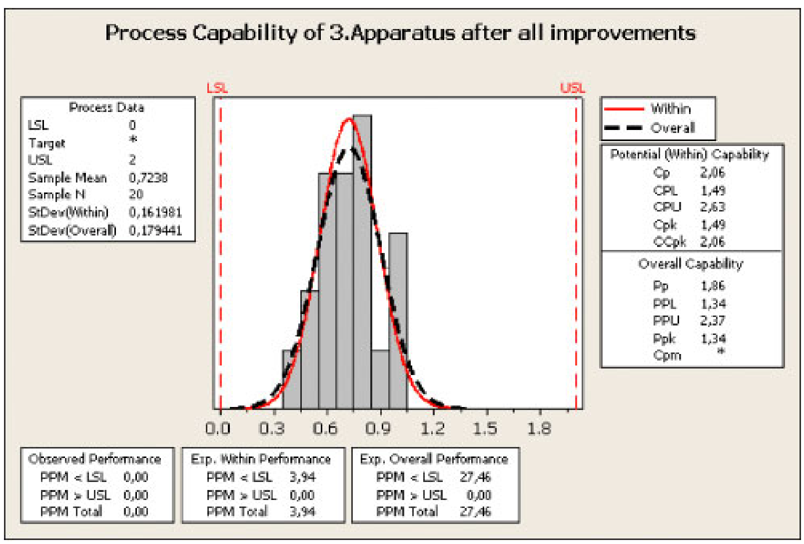

Figure 16. Process capability of the third apparatus after all improvements

2.5. Control phase

Control phase is obviously the most important stage of six sigma methodology. At this stage all the activities that are accomplished in the other four stages are investigated so that their permanence should be sustained. For this purpose, first of all achieved profit levels after the improvements are evaluated and in order to keep this profit stable and also to increase it, some action plans are prepared. The action/control list related with these plans can be seen in Table V.

As a result of these five phases of DMAIC, a comparison of sigma values based on the current and improved status is given in Table VI. For this calculation, the process has been assumed to have 1.5σ shift. From this table it is concluded that the sigma level has increased from about 2.5 to 5.56, which is a very

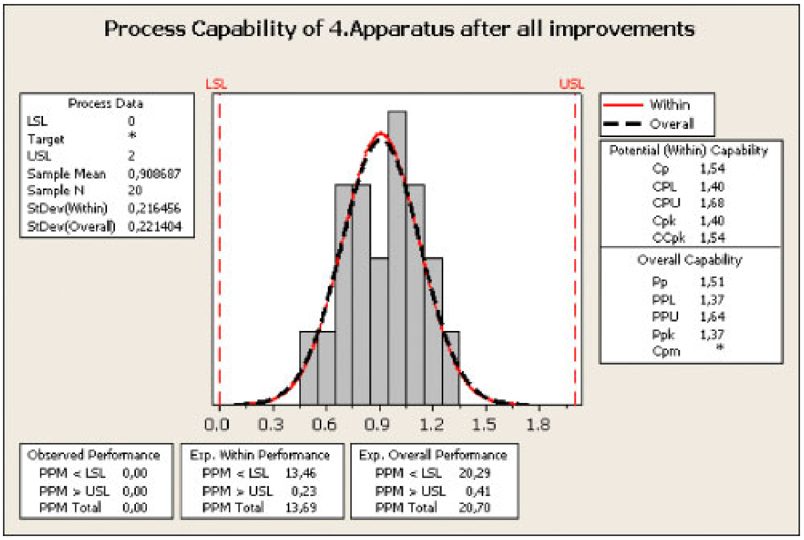

Figure 17. Process capability of the fourth apparatus after all improvements

Table V. Action/control tracking list

Problem tracking number	Problem	Action	Responsible	Target date	Closing date
1. Improvement	Revision of the periodical maintenance term in operation description sheet (ODS)/work instruction	Document revision and training	Manufacturing engineer (metal)	W38	W37
2. Improvement	Declaration of quality alarm for fixing the new parameter values	Document creation and training	Quality engineer (metal)	W37	W38
3. Improvement	Creation of the urgent case action plan	Document creation and training	Production and quality team	W38	W39

Table VI. Comparison of sigma values

Fixture (apparatus)	Current (σ)	After improvement (σ)
1. Apparatus	1.74	5.59
2. Apparatus	2.27	5.51
3. Apparatus	3.20	5.53
4. Apparatus	2.79	5.60
Average	2.5	5.56

good improvement. For further comparison, the number of reworked quantities per apparatus is given in Table VII. This table indicates an average improvement of 47.83%, which is greater than the project target of 40%.

Table VII. Comparison of reworked quantities per each apparatus

Number of reworks per apparatus	Current	After improvement	Improvement percentage %
Y_{C1} = number of the reworked parts arise from apparatus #1	2.21	1.02	46.18
Y_{C2} = number of the reworked parts arise from apparatus #2	1.93	0.98	50.51
Y_{C3} = number of the reworked parts arise from apparatus #3	1.41	0.72	51.38
Y_{C4} = number of the reworked parts arise from apparatus #4	2.10	0.91	43.25
		Average	47.83

3. CONCLUSIONS

Six sigma is a fundamental continuous improvement methodology aimed on reducing the variation and waste on processes by utilizing statistical methods and techniques efficiently. Although this is the case and six sigma methodologies are gaining broader recognition in business organizations these days, it is not easy to find a detailed real-life case study in literature. In this paper, an application of six sigma methodology for reducing the quantity of rework parts for a robotic arc welding process is given. The phases of six sigma and their results are indicated in detail. It presents the project selection phase and then employs the six sigma DMAIC methodology by illustrating its phases, i.e. define, measure, analyze, improve and control. Several statistical tools and techniques were employed during the course of the project. As a result, the process capabilities and the sigma levels increased significantly, and quantity of reworked parts decreased. The project target was achieved. In addition to these results, trivial benefits such as an increased process knowledge and use of statistical thinking to solve engineering problems were also achieved. Based on the results of this project new ideas are being formed and further projects will follow.

4. LESSONS LEARNED

While applying the six sigma methodology on this process, many problems had been faced. Some of the problems and experiences gained from this project are listed as follows:

- A strong management support is needed for a successful implementation, because it will speed up the process if the solution to the root cause of the problem needs investment.
- In order to obtain management acceptance and dedication, the first several six sigma projects should be chosen such that their results will yield some kind of economical improvement. If this can be accomplished, the results will have a significant effect on the management and the entire company may shift to using six sigma instead of other quality methods.
- Six sigma projects should be undertaken by a group that can devote full-time on the project. In most of the small and medium enterprizes these projects are undertaken as part-time because of a limited number of qualified personnel. This constraint can be eliminated by providing six sigma education to most of the white collar engineers and some of the blue collar expert operators. Then, many groups can be formed to implement successful projects.
- Most of the operators resist a change and it is usually very difficult to obtain relevant and accurate data. In order to overcome this issue training is needed.
- Using the statistical methods in a systematic manner in six sigma is more powerful than the other old techniques, as it is usually very difficult and time consuming to find a way to analyze the problem with traditional methods and without a systematic approach.

- The results obtained by this project will provide start-up data for further implementations. For example, in future layouts the results in this paper will be used as a guideline for new welding fixtures.

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DOI: 10.1002/qre

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