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CASE STUDY

Applying Six Sigma and design of experiment to improve coil manufacturing processes – a case study in KSVN

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The company under study specializes in manufacturing parts for the automotive industry. The manufacturing process of the company has the problem of high failure rates (FRs), resulting in high-quality failure costs and low profit. In this research, Six Sigma was used to solve the problem with the objective to reduce the FR. The research methodology was based on the define measure analyze improve control (DMAIC) procedure, including five steps: define, measure, analyze, improve, and control. The tools used in the steps of the DMAIC procedure include cause and effect diagrams, Pareto diagrams, and control charts. In addition, design of experiments (DOEs) was also used to optimize the process parameters. After applying Six Sigma and DOE, the FR of the coil manufacturing process reduced by nearly 50%, from 10.27 to 5.33%.

Keywords: Six Sigma, DMAIC, DOE, ANOVA, SIPOC, project charter, Pareto charts, control charts

Introduction

Nowadays, businesses all over the world are facing the challenge of quality. With globalization, competition and demand are increasing. Quality is no longer a purely technical issue but has become a top strategic issue related to the survival of businesses.

Kyoshin Vietnam (KSVN) is a company specializing in manufacturing components for the automotive industry, with many different types of products. Currently, the company is also striving to build a zero defect production system according to a quality management system that meets international standards.

Although the company's quality control process is implemented quite strictly, the implementation in some departments is still not effective. In addition, due to many different factors, the quality of some of the company's products has not yet reached the set target, the failure rates (FRs) in the process are still high, and there are still unconformable products being moved to the next process and even to customers.

Mold Coil Sub Assy (C23 H5) is a new product line, requiring high precision, very strict technical requirements, and very strict quality standards. Although it has gone through the trial production stage, the product quality is still unstable; there are still many scraps in the assembly and external plastic injection stages.

The current FR of this product is 10.27%. This is a very high rate and is unacceptable compared to the company's quality system. The company currently has to produce more than the order to compensate for the defect, so the product cost is high and causes a lot of waste. The company wants to reduce the FR to below 6%.

Six Sigma is a popular method widely used in quality improvement. In this article, the application of Six Sigma is discussed to improve the production process of KSVN, identify and eliminate the causes of failure, and minimize waste for the above product line, with the goal of reducing the FR to below 6%.

Literature review & research methodology

Literature review

In the mid-1980s, Motorola pioneered the use of the Six Sigma concept in measuring product quality. In the mid-1990s, General Electric was considered a model company in implementing Six Sigma projects, and the company's CEO, Jack Welch, used Six Sigma as the company's popular quality improvement solution. Later, the quality improvement solution based on Six Sigma was applied in many companies, from manufacturing to services such as Texas Instrument, Boeing, IBM, Xerox, Citibank, Raytheon, etc.

Six Sigma evolved from a simple capability measure into an improvement methodology aimed at achieving unprecedented levels of quality by focusing on critical characteristics and identifying and eliminating the causes of defects. Six Sigma aims for a FR of a few parts per million by effectively applying statistical principles and tools for diagnosis, problem solving, and system improvement (1).

Soar and Balanescu (2) introduced the history of Six Sigma as well as highlighted the benefits of applying Six Sigma. In addition, the define measure analyze improve control (DMAIC), design for six sigma (DFSS), define measure analyze design verify (DMADV), identify design optimize validate (IDOV), and difference-in-differences (DIDES) methods were introduced depending on the purpose of use. In which, the DMAIC process—Define, Measure, Analyze, Improve, and Control—was described specifically, and they also introduced how to apply Six Sigma in process management.

Gupta (3) presented a quality improvement study applied at a yarn manufacturing company based on Six Sigma methodologies. He applied the DMAIC process to identify, the cause of the problem and improve quality, reducing the percentage of defective yarn products.

Soković (4) presented a Six Sigma project, undertaken within the company for the production automotive parts, which deals with the identification and reduction of production cost in the deburring process for gravity die-castings and the improvement of the quality level of produced parts.

Ferreira and Lopes (5) used Six Sigma methodology in a semiconductor company to simplify the scrap request process of electronic controllers of wall-hung gas boilers and to reduce its processing time. Through the elimination of problems identified and resolved using the DMAIC procedure, the processing time of scrap requests was substantially reduced, allowing for high cost savings.

Hung and Sung (6) used Six Sigma to solve an underlying problem of reducing process variation and the associated high FR in a food company in Taiwan. The DMAIC phases were utilized to decrease the FR of small custard buns by 70% from the baseline of 0.45% to below 0.141%.

Kurnia et al. (7) determined the level of sigma defects of socks and provided suggestions for quality improvements in reducing the percentage of sock defects. The methodology used in the study is the DMAIC approach. The results of this study are that the level of Sigma increased from 3.7017 to 3.9614, and the percentage of sock defects decreased from 11.08 to 5.54%.

Nguyen Nhu et al. (8) applied Lean Six Sigma to improve garment production processes. The research methodology was based on Lean Six Sigma theory, with the platform of the DMAIC procedure. The tools used in the steps of the DMAIC procedure include cause-and-effect-diagram, Pareto diagram, value stream management, work design, single-minute exchange of dies (SMED), line balancing, Kanban systems, first in first out (FIFO), autonomous maintenance, visual management, design of experiments (DOEs), and control charts. After applying Lean Six Sigma tools, the company had reduced the production lead time by 89.21% from 279 to 30.1 min, reduced the production cycle time by 36% from 25 to 16 s, and reduced the process defect rate by 37.45% from 14.9 to 9.32%.

Research methodology

Six Sigma is a rigorous, data-driven improvement approach with specific problem-solving steps. Six Sigma uses sophisticated statistical tools with a tightly structured problem-solving approach based on the scientific research methodology, including five steps:

1. D – Define
2. M – Measure
3. A – Analyze
4. I – Improve
5. C – Control

The define step identifies the problem, the objective, the product line to be improved, and the scope of the manufacturing process. Tools used in the define step include Pareto charts, suppliers inputs process outputs customers (SIPOC), and project charter.

The measure step collects data to measure the actual capacity of the process through the capacity of the stations. The tool in the measure step is a check sheet to collect data.

The analysis step finds the root causes of the problem, from which solutions are proposed to solve the problem, including the following sub-steps:

1. Identify critical stations with high FRs.
2. Identify root causes in the critical stations.
3. Identify solutions for the root causes.

Tools used in the analysis step include cause effect diagram (CED), Pareto charts, and 5 Whys.

The improvement step implements the solutions identified in the analysis step to improve the process to achieve the goals set in the define step. DOEs is used in this step to optimize the process parameters.

The control step controls the process to maintain improved results. Control charts are tools used to control critical quality characteristics of the process.

The DMAIC procedure would be used to improve the production process of KSVN as presented in the following sections.

Define

Low quality reduced external customer satisfaction and caused great waste for the company. The company had nine product families, including C23, B71, B60, 7PC, V13, CB7, G50, and A01. For product line selection, the Pareto chart of revenue R and cumulative revenue percentage CRP of product families was shown in Figure 1.

The Pareto chart of FR and cumulative failure rate (CFR) product families was shown in Figure 2.

From the two Pareto charts in Figures 1 and 2 above, it could be seen that product family C23 has both the highest revenue and the highest FR. Therefore, product family C23 is selected for further analysis. Product family C23 included many products with CFRs as shown in Table 1 below.

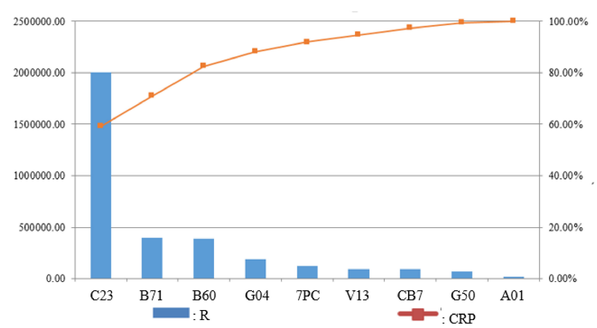

FIGURE 1 | Pareto chart of revenues.

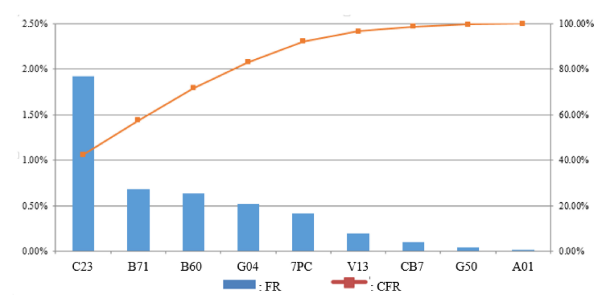

FIGURE 2 | Pareto chart of FRs.

TABLE 1 | CFRs of products in the C23 family.

i	Products	FRs (%)	CFRs (%)
1	C23 H5	10.27	59.65
2	C23 H6	2.64	74.96
3	C23 H7	2.28	88.20
4	C23 H8	2.03	100.00

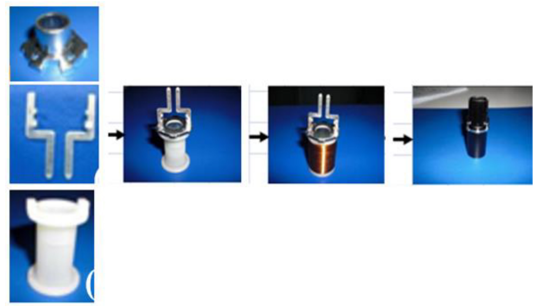

FIGURE 3 | Parts in C23 H5.

Supplier	Inputs	Process	Outputs	Customer
KK	Materials Machines Workers	W1	C23 H5	KK
		W2		
		W3		
		W4		
		W5		
		W6		
		W7		
		W8		
		W9		
		W10		
		W11		

FIGURE 4 | The suppliers inputs process outputs customers (SIPOC) diagram of the selected product.

From Table 1, C23 H5 was the product with the highest FR. This was also a new product with unstable quality compared to the remaining products in the C23 family. This product was required to satisfy strict technical requirements from customers. Therefore, this product was selected for further research. C23H510 0020 included parts and semi-products as described in Figure 3.

In order to get an overview and the scope of the manufacturing process of the selected product before starting the steps of measuring, analyzing, and improving the process, the SIPOC diagram is used as shown in Figure 4 below.

KK was the supplier and also the customer. Inputs include materials such as copper wire, plastic beads, etc., from suppliers, and machinery such as welding machines, wire winding machines, plastic injection machines, testing machines, and packaging machines. The process included 9 stations as in Table 2. The output was C23 H5.

From the information defined above, the article briefly describes as in the project charter with voice of customer, critical to quality, objective, and scope in Figure 5 below.

TABLE 2 | Work stations in the process.

Work stations	Functions
W1	Bobin plastic injection
W2	Core stamping
W3	Terminal stamping
W4	Core assembly
W5	Terminal assembly
W6	Wire winding
W7	Soldering
W8	Excess copper wire processing
W9	Inspection of internal diameter & appearance
W10	External plastic injection
W11	Wavelength, resistance inspection & packaging

Project charter	
Project	Applying Six Sigma to improve manufacturing process in KSVN
VOC	Low quality reduces external customer satisfaction and causes great waste for the company.
CTQ	Faiture rate
Objective	Reduce failure rate
Scope	Manufacturing process of C23H510 0020

FIGURE 5 | The Six Sigma project charter.

TABLE 3 | The FRs of the stations in the process.

Work stations	Functions	FR (%)
W1	Bobin plastic injection	0.03
W2	Core stamping	0.06
W3	Terminal stamping	0.04
W4	Core assembly	0.06
W5	Terminal assembly	0.06
W6	Wire winding	3.86
W7	Soldering	0.64
W8	Excess copper wire processing	0.10
W9	Inspection of internal diameter & appearance	0.15
W10	External plastic injection	5.21
W11	Wavelength, resistance inspection & packaging	0.08
	TOTAL	10.27

Measure

In order to measure the process capability, the FR of the stations in the process was collected as shown in the following **Table 3**.

It was found that the process FR was 10.27%, which is quite high. After measuring the current situation, the goal was set to reduce the product FR to below 6%.

Analysis

The FRs were arranged in descending order as shown in the following **Table 4**.

In order to effectively reduce the FR, stations with high FRs will be analyzed. With the goal of reducing the FR to below 6%, stations of external plastic injection and wire winding would be selected for further analysis.

The external plastic injection station

The types of failure at the external plastic injection station, along with the FR and CFR, were collected and statistically recorded as in **Table 5**.

The Pareto chart was constructed from the data in **Table 5** as in **Figure 6**.

The CFR of three types of failures, including copper protrusion, mixed materials, and plastic scratches, accounted for 88.4%. These three types of failures were selected for further analysis to find the root cause to eliminate these types of failures.

TABLE 4 | The FRs arranged in descending order.

i	Work stations	FR (%)
1	External plastic injection	5.21
2	Wire winding	3.86
3	Soldering	0.64
4	Inspection of internal diameter & appearance	0.15
5	Excess copper wire processing	0.10
6	Terminal stamping	0.04
7	Inspection & packaging	0.08
8	Core stamping	0.06
9	Terminal assembly	0.06
10	Core stamping	0.06
11	Bobin plastic injection	0.03

TABLE 5 | Failures in the external plastic injection station.

Fi	Failures	FR (%)	CFR (%)
F1	Copper protrusion	61.19	61.19
F2	Mixed materials	16.99	78.18
F3	Plastic scratches	10.21	88.40
F4	Plastic burrs	2.15	90.55
F5	Terminal staggered	1.85	92.40
F6	Product dropped	1.69	94.08
F7	Scratch surface	1.49	95.57
F8	Broken wire	1.38	96.95
F9	Lack of plastic	1.23	98.18
F10	Oil stains	1.06	99.24
F11	Others	0.76	100

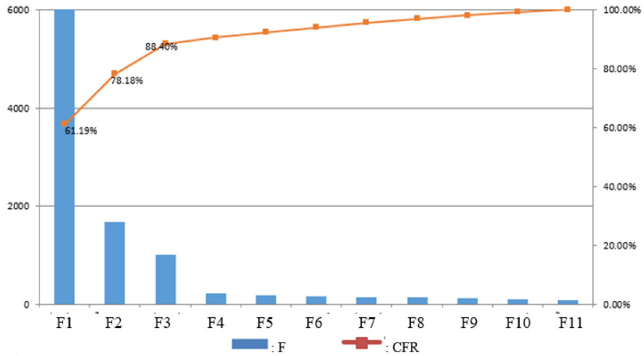

FIGURE 6 | Pareto chart for failures in the external plastic injection station.

Copper protrusion

Copper protrusion occurred when the outer plastic thickness covering the coil was not sufficient or the amount of plastic injected was insufficient or uneven. Using the brainstorming method combined with consultation with experts in the production department, the possible causes of this type of failure were presented in a fishbone diagram. Data collection and analysis showed that the two main causes, accounting for nearly 80% of copper protrusion, were as follows:

- Inadequate injection plastic amount
- Improper raw material drying time.

The 5 whys method was used to determine the root causes of the two main causes. Ultimately, the root causes of the problem were as follows:

- High mold temperature during production
- No drying time was recorded on the drying drum.

Mixed materials

Using the brainstorming method combined with consultation with experts in the production department, the possible causes of mixed materials failure were presented in a fishbone diagram.

Data collection and analysis showed that the two main causes, accounting for 62.96% of mixed materials, were as follows:

- Poor mold cleaning
- Inappropriate tools used

Continue to analyze these two main causes to find the root causes. The root causes were as follows:

- Improper gloves
- No mold cleaning equipment.

Plastic scratches

Using the brainstorming method and consulting experts in the production department, the failure of plastic scratches created when taking out the product, the worker collided the product with the mold wall and dropped the product, colliding with hard objects around. The root cause is due to the worker's incorrect operation.

Wire winding station

The possible causes for failures in the wire winding station included broken wire, scratched wire, improper winding, and some other causes. Among these causes, improper winding was the main cause, causing 90% of the failures in the wire winding station. Further analysis shows that the root causes were due to improper winding tension and the number of turns.

Table 6 summarized all root causes after the analysis step. These root causes would be addressed in the improvement step below.

Improve

After determining the root causes of the problem, solutions to solve the problem were as shown in Table 7.

Improvement solutions were specifically described in Table 7. The DOE solution at the winding station would be implemented to determine the tension and number of winding turns to minimize the FR at the winding station.

The technical parameters of tension T and number of windings N of the wire winding process were given in Table 8.

The experiment was performed with two input variables and one output variable. The input variables or factors were tension T and number of windings N. The output variable was the station's FR. Tension T was tested with seven levels,

TABLE 6 | The root causes after analysis.

Stations	Failures	Main causes	Root causes
External plastic injection	Copper protrusion	Inadequate injection plastic amount	High mold temperature during production
		Improper raw material drying time	No drying time recorded on the drying drum
	Mixed materials	Inappropriate tools used	Inappropriate gloves
		Poor mold cleaning	No mold cleaning equipment
	Plastic scratches	Plastic scratches	Workers' incorrect operation
Wire winding	Wire winding failure	Improper winding	Incorrect tension and number of turns.

TABLE 7 | The root causes and solutions to solve the problem.

Root causes	Solutions
High mold temperature during production	– Plan to clean the mold periodically. – Plan to check mold temperature at the beginning and middle of the shift. – Warning when the temperature is outside the allowable limit.
No drying time recorded on the drying drum	– Determine and display drying time in the drying bin. – Training & job guidance.
Inappropriate gloves	– Use suitable gloves, with the rubber part above the fingertips. – Change gloves periodically.
No mold cleaning equipment	Use an air spray gun to clean the mold to blow away any metal particles before inserting the coil and after removing the product.
Workers' incorrect operation	– Worker training. – Regularly check workers' operations when taking out products.
Incorrect tension and number of turns	DOE

TABLE 8 | Technical parameters of the wire winding process.

Parameters	Specification tolerance
T (g)	550–650
N (turns)	625–635

TABLE 9 | Input factors and their levels.

Factors	Factor levels
T (g)	570, 580, 590, 600, 610, 620, 630
N (turns)	626, 628, 630, 632

number of winding N was tested with four levels, as shown in **Table 9**.

The experiment was carried out with three repetitions in each factor's combination; the total number of experiments was:

$$N = 7 \times 4 \times 3 = 84.$$

The experimental sequence was conducted randomly. Experimental results were analyzed with the support of Minitab software. The analysis of variance (ANOVA) table was as shown in **Figure 7**.

From the ANOVA table above, with a significance level α of 0.05, we see that the input factors, as well as the interactions between factors, all affected the FR. The number of turns N has the strongest influence, followed by tension T and finally the interaction $N*T$ between the number of turns and tension.

General Linear Model: FR versus T, N

Factor	Type	Levels	Values
T	fixed	7	570, 580, 590, 600, 610, 620, 630
N	fixed	4	626, 628, 630, 632

Analysis of variance for FR, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
T	6	51.9521	51.9521	8.6587	13.85	0.000
N	3	72.0174	72.0174	24.0058	38.40	0.000
T*N	18	36.7515	36.7515	2.0418	3.27	0.000
Error	56	35.0117	35.0117	0.6252		
Total	83	195.7328				

S = 0.790702 R-Sq = 82.11% R-Sq(adj) = 73.49%

FIGURE 7 | The ANOVA table of the experiment.

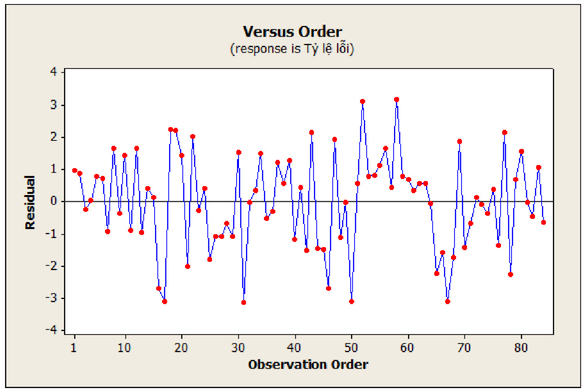

FIGURE 8 | Residual run chart.

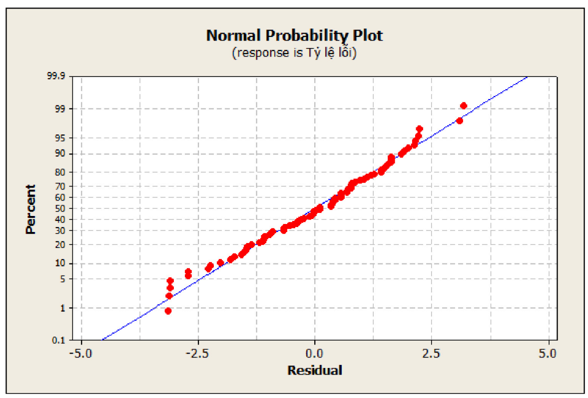

FIGURE 9 | Normal probability plot.

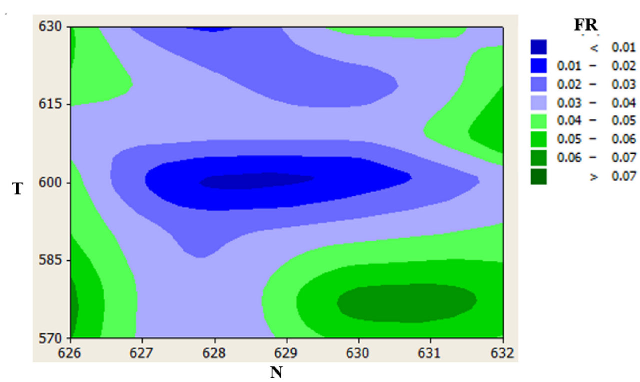

FIGURE 10 | The contour plot of FR according to T and N.

TABLE 10 | The FRs before and after improvements.

i	Work stations	FR (%)	
		Before	After
1	External plastic injection	5.21	2.71
2	Wire winding	3.86	1.42
3	Soldering	0.64	0.64
4	Inspection of internal diameter & appearance	0.15	0.15
5	Excess copper wire processing	0.10	0.10
6	Terminal stamping	0.04	0.04
7	Inspection & packaging	0.08	0.08
8	Core stamping	0.06	0.06
9	Terminal assembly	0.06	0.06
10	Core stamping	0.06	0.06
11	Bobin plastic injection	0.03	0.03
	Total	**10.27**	**5.33**

The experimental model was validated with the residual run chart in **Figure 8** and the normal probability pin **Figure 9**.

From the graphs, it could be seen that experimental errors varied randomly and followed a normal distribution. Experimental results could be used to determine input variables to optimize output variables.

The contour plot of FR according to tension T and number of windings N was shown in **Figure 10**.

With the goal of minimizing the FR, the optimal value of the input variables corresponded to the dark blue area in the middle of the chart. This area had the lowest FR (FR < 0.01). This optimal region corresponded to a tension that fluctuated slightly around the value 600, and the number of turns was between the values 628 and 629. The selected values were as follows:

$$T = 600$$
$$N = 628$$

After applying improvement solutions, the FRs before and after improvements at the two critical stations, external plastic injection and wire winding, were estimated as shown in **Table 10**. The remaining stations had unchanged FRs.

It is seen that after improvement, FR decreased from 10.27 to 5.33%, achieving the set goal of reducing FR to less than 6%.

Control

Process control was carried out at the injection and winding stations to maintain improved results.

Control in plastic injection station

At the plastic injection station, the controlled quantities included the plastic injection FR and the plastic layer thickness. The plastic injection FR was controlled by the proportional chart proportional control chart (PCC) 01 with variable control limits. Data were collected, control limits were established, and the PCC 01 chart for controlling the injection FR was shown in **Figure 11**.

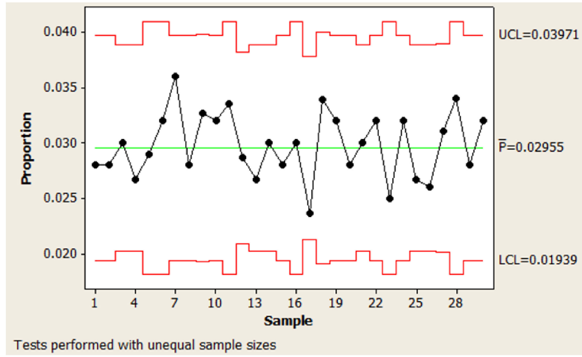

FIGURE 11 | PCC 01 chart for controlling the injection FR.

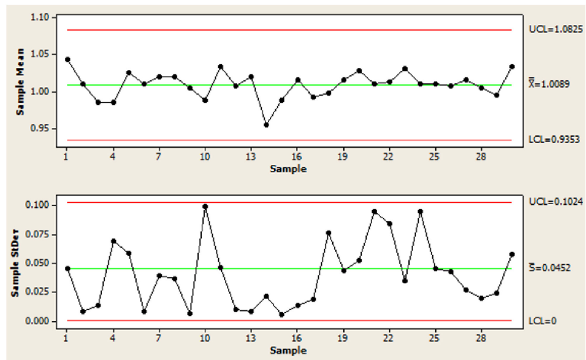

FIGURE 12 | Control charts for controlling the layer thickness.

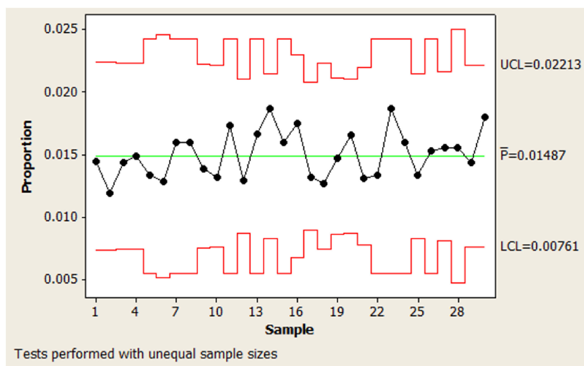

FIGURE 13 | PCC 02 chart for controlling the winding FR.

The plastic layer thickness was controlled by a pair of variable control charts, including sample mean chart mean control chart (XCC) and sample standard deviation chart standard deviation control chart (SCC). XCC was used to control the layer thickness expectation; SCC was used to control the layer thickness variability. Data were collected, control limits were established, and the control charts were as shown in **Figure 12**.

Control in winding station

At the winding station, the controlled characteristic was the winding FR. The winding FR was controlled by the proportional chart PCC 02 with variable control limits. Data were collected, control limits were established, and the PCC 02 chart for controlling the winding FR was shown in **Figure 13**.

Conclusion

The article discusses the application of DOE to improve the coil manufacturing process of the C23 H5 product in the KSVN company. The research methodology was based on Six Sigma thinking, with the platform of the DMAIC procedure. The tools used in the steps of the DMAIC procedure include SIPOC, project charter, cause and effect diagram, Pareto diagram, DOEs, and control charts. After applying Six Sigma tools, the FR of the process reduced from 10.27 to 5.33%, achieving the initially set goal.

DOE had been applied to determine parameters at the winding station to minimize the FR at this station. Control charts had been used in the control phase to maintain improved results by controlling important process characteristics.

Methods discussed in the article still had many limitations. Improvements were only made at plastic injection and wire winding stations. In addition, the control step used only control charts to control important process variables. Further development includes implementing improvements at the remaining stations to further improve the sigma level of the production process and using statistical tools to control the entire process.

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Conflict of interest

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

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