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Application of Statistical techniques in improving the manufacturing operations

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Abstract

The central problem in lack of quality is the failure to understand variation. Variation is the main enemy of achieving quality in the production. Statistical techniques are used to minimize the process variability for achieving high efficiency and quality of the products. This work focuses on identifying and reducing the variation in the manufacturing process of fan blade. The whole process of blade manufacturing is investigated to detect the sources of variations in the blades' weight. Taguchi method is applied in manufacturing processes for well identifying all operating parameters which critically affecting the behavior of the process, and try to improve those operating parameters. The optimization of the parameters of the experiment is applied with Minitab 19 statistical package software. The achieved results showed that the optimization parameters of the electrostatic painting machine are at a voltage of 100 KV, speed of 35 m/s, a distance of 300 mm, and a pressure of 2.5 bar. The achieved results showed that there is a significant improvement in the standard deviation of coating thickness by 52%, and an increase in the process performance indices (C_{pk}) from (-0.21 to 0.52). Similarly, the process capability indices (C_p) are increased from (0.47 to 1.38). These results indicate that the process of electrostatic painting has a great reduction in variability. Also, the results showed a significant reduction in powder consumption which led to a significant decrease in the cost of blade paint by 40%, with total annual saving of 3,456,000 LE/Year.

Keywords: Statistical techniques, Variation Reduction; Taguchi Method.

1 Introduction

Statistical approaches are critical in quality control and process variability reduction. Statistics is a set of methods for making judgments about a process. Statistics are concerned with examining data acquired from a collection of product samples. Statistics are the primary means of sampling, testing, and evaluating a product. The data's information controls and improves the process and product [1]. Taguchi demonstrates how the statistical design of trials can aid in producing high-quality, low-cost products. His method is centered on addressing the root causes of the fault and making the product's performance insensitive to variation. The design of experiments is an effective statistical strategy for discovering the ideal process factor settings and, as a result, improving process performance and lowering process variability [2]. The manufacturing process of ceiling fan blades consists of multi stages processes. To reduce the variation range of fan blades it is important to understand its manufacturing processes. The impact of particle movement and distribution on the film thickness of electrostatic paint has been investigated by [3]. This work is carried out in the production line of ceiling blade fane; this production line has many defective products. After taking samples from the blades, it was found that the weight of blades varies from 590g-635g. This variation in weight causes unbalanced rotation of the ceiling fan, which can lead to the following problems: vibration, noise, and reduced life of the final product. The collected data are analyzed by using control charts and process capability which, reveals that the source of variation is the electrostatic painting process. Taguchi method is used to identify and reduce the variation in this process.

2. Literature review

2.1 Ceiling Fans Manufacturing Processes.

The production processes of a ceiling fan comprise broadly two stages; manufacturing of components and assembling of components into a finished product. The raw material is a sheet. The manufacturing process of fan blades starts with the pretreatment of raw materials. After cleaning the raw material, the metal sheet is forced into the die to take the shape of the blade through a casting process. After that, the blades are further treated to give smoothness to their surface [4]. The complete ceiling fan manufacturing process is illustrated in figure 1.

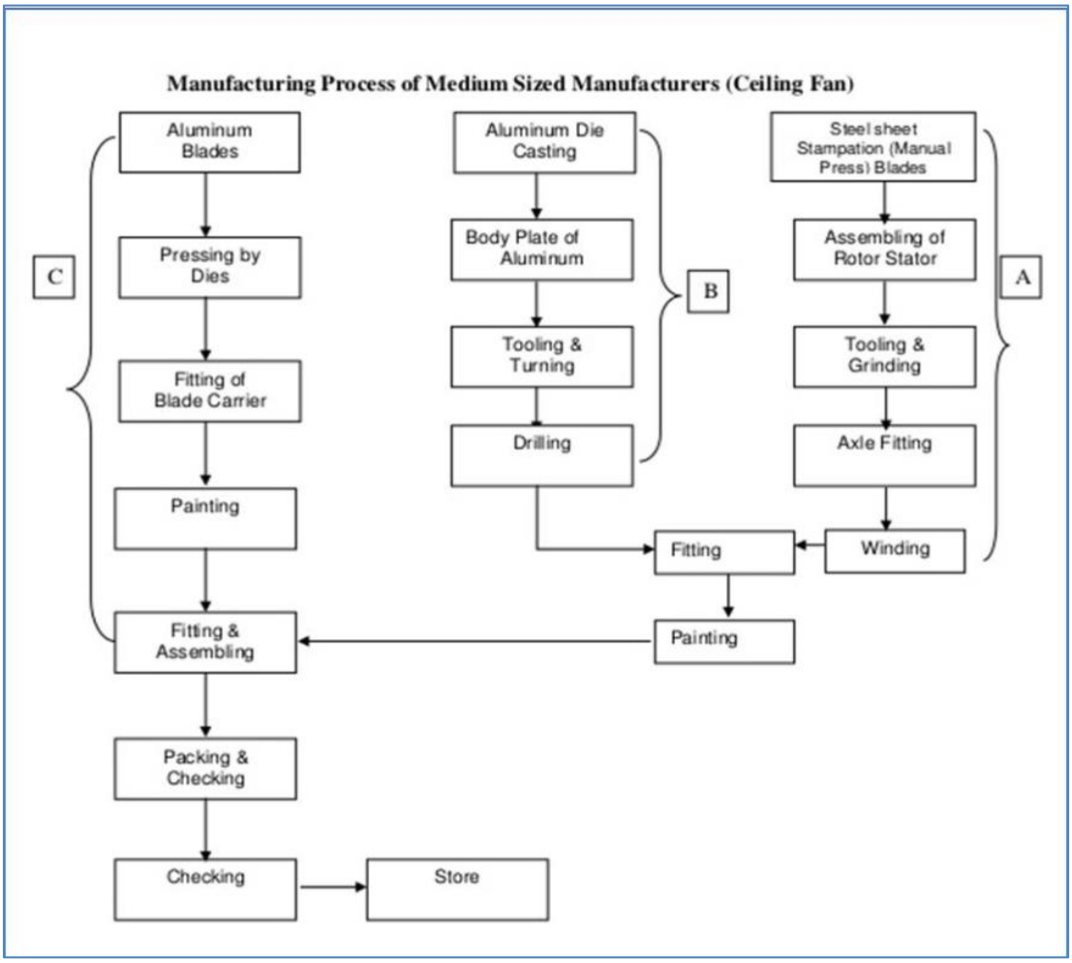


Fig. 1 Different processes of ceiling fan manufacturing [4]

2.2. Quality characteristic of Blades

The effective design of the fan blade begins with determining the fan blade's basic functions. The primary duty of a fan is to create considerable air flow in a place, which should be done over a long period of time at movable revolution per minute. The ability of fans to move air efficiently and quietly is used to rate their quality. Ceiling fan blade pitch, length, and number, as well as revolutions per minute (rpm), are used to assess fan quality. Pitch refers to the angular edges of ceiling fan blades, which are extremely important for proper air circulation [4]. Because of the form, the blade may apply pressure on the air in front of it, forcing it downward. The more air replenished, the higher the pitch. The pitch of high-quality ceiling fan blades is (12-14) inches. Low blade pitches of 8 or 10 degrees result in poor performance. While short ceiling fan blades with low pitches can spin at high speeds, they do not generate much air circulation and are noisier even at slower speeds than fans with longer blades and higher pitches. In painting the blades of the ceiling fans, the unbalanced spraying of paint at different parts of the blades may result in the weight variations of the blade at different sections which may lead to the unbalanced movement of the blades when the fans are in operation. This unbalanced movement of blades is called wobbling. The wobbling of the fan is typically caused by out of weight balance blades. There could be two possible reasons for the weight variation of the fan blades. First, the electrostatic painting process can cause a change in weight at different points of the blades due to over-spraying or thing paint film at different points of the blades. Second, the blade manufacturing process in which the role of the die is important [5].

2.3 Punching process of blade manufacturing

The die gives the final shape to the blades, any uneven stresses or application of uneven forces at different parts of the blades can lead to weight variations of the blades [6]. Figure 2 show the component of the die and punch assembly.

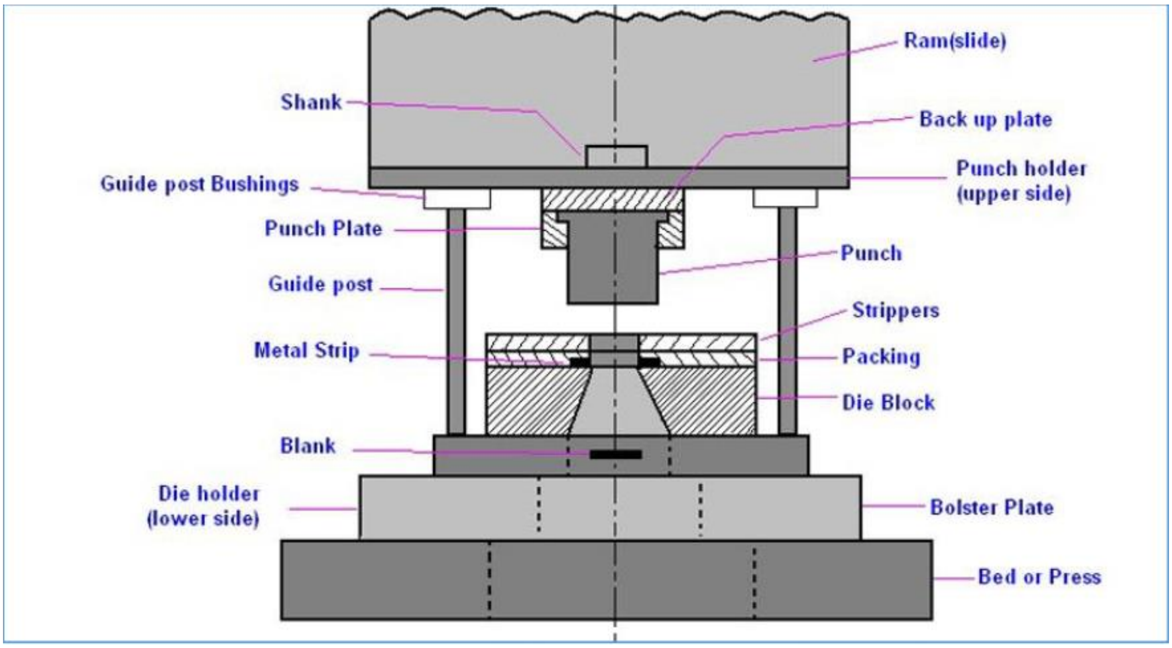


Fig. 2 Component of dies and punch assembly [6]

Parameters affecting the final shape of the blades:

- **Radius on punch:** When sheet metal is folded over the punch nose, a shaper radius demands more effort, which may result in excessive thinning or ripping at the bottom of the cup. To avoid excessive thinning, make a punch with a nose radius of 4-10 times the sheet thickness. It may be essential to generate over a large radius and then "Re-strike" in order to build the correct radius. [7].
- **Draw radius on the die:** This radius should, in theory, be as large as feasible to provide for complete sheet metal flow flexibility. Plastic flow of the metal is caused by the draw ring or die, resulting in inside compression and exterior thickness. The draw radius is four times the thickness of the material. When drawing shallow cups of heavy gauge metal without a blank holder, the draw radius can be expanded to 6 to 8 times the metal thickness. [7].
- **Draw speed:** Essentially, the draw operation is slow and progressive, with substantial strain on the material. Material must enter the die at a consistent rate. As a result, non-uniform speed might lead to variety and quality difficulties [7].
- **Cracking load:** The maximum permitted drawing load is limited by the load that the sheet can transfer in the punch radius region or during the transition from the cup wall to the bottom radius, which is known as a cracking load. It must never be less than the maximum drawing load. [8].
- **Die clearance:** If the die clearance is too large, the component does not form a true cylinder and the cup's upper edge stays inflated. If the die clearance is too tiny, ironing can occur, increasing the drawing load and increasing the risk of cracking [9].
- **Metal flow during drawing:** The flat circular blank is drawn into a flat-bottomed cup by pressing a punch against a flat circular blank which lying on a die. The punch makes contact with the blanks, forming the flat bottom of the cup that is not distorted by the punch. As the punch travels downward, more metal is pulled over the die radius, which is eventually straightened. In other words, the outside border of the blank is being drawn toward the punch [10].

2.4 Electrostatic Painting Process

The basic concept of electrostatic painting process is using a magnetic field to achieve permanent layer of paint on the metals or polymers. This process depends on the rule of opposites' attraction. The attraction is created by applying a negative charge to the object to be painted and a positive charge to the paint, resulting in a durable, smooth, hard paint finish that is plated on [11]. The electrostatic field, like the magnetic field, is formed when an object becomes charged. A negatively charged object has more electrons than it requires; a positively charged thing has fewer electrons. [12] The electrostatic painting concept began with hanging the part on the hook and charging the powder with a high voltage generator, and then oppositely charged particles will be drawn to one another as seen in figure 3. The paint is positively charged and applied using a spinning nozzle. The positive and negative charges attract the paint to the metal surface like a magnet. The paint is dragged around the item, completely covering the surface, due to the strong attraction between the opposite charges. Overspray is not an issue because the paint is statically bonded to the metal from all directions. The paint would be sprayed onto the fence, wrapping around and sticking to the rear of each panel. Because there would be no overspray, there would be no mess in the immediate region, and very little, if any, paint would be lost or used [13]. Electrostatic painting has various benefits and advantages; it offers a smooth, durable enamel finish, the thickness of the paint is easy to adjust, the surface of the painted object is sanitary since it is non-porous, and it is resistant to cleaning agents [14]. Electrostatic painting is extremely effective, resulting in a perfect surface. Because of the design and development of transportable painting machinery, coatings may now be electrostatically applied almost anywhere [15]. If electrostatic painting is not applied correctly, it may have several drawbacks in producing smooth or even thick paint coatings. Predicting the thickness of paint has various practical advantages, including ensuring that the correct amount of paint is applied to achieve the performance attributes of the coating. Less material will be used as a result, and material prices will be reduced. Coating thickness is proportional to dry time, recoat time, and aesthetics.

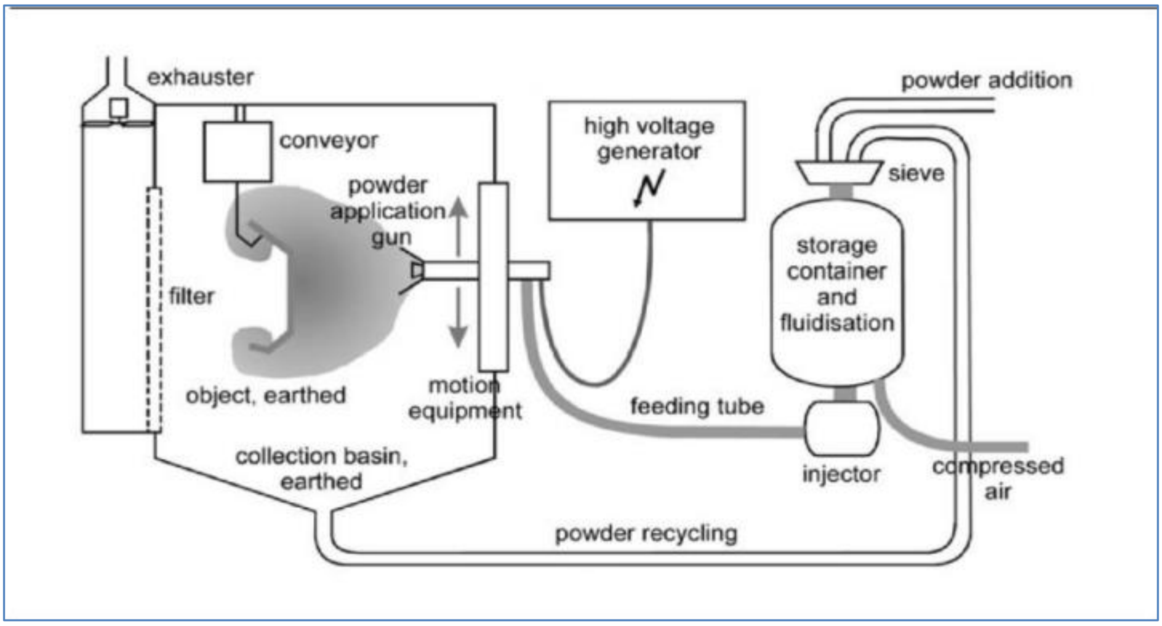


Fig. 3 Electrostatic painting system [13]

2.5 Factors affecting the electrostatic process

Many factors must be considered when optimizing the electrostatic process to have the even thickness of film or reduce the weight variations in the ceiling fan blades [16]. These factors are related to configuration of part, process parameters, or powder material.

A. Effects of Configuration of parts to be painted:

Configuration of part is important because the film thickness is easiest to control on round parts (round tubing and wire goods) since they have few edges and no corners. Theoretically, the film thickness on all areas of a round part should be same. Parts that have complex configuration have many edges or corners or both. Boxes are perhaps the most complex parts because they have more edges and corners than other parts. The presence of edges increases coating thickness and edges [17].

B. The Faraday Cage Effect:

When painting more intricate surfaces with recessed sections, the Faraday Cage Effect may arise. When negatively charged paint shoots from the gun, it seeks out the first positively charged grounded item. When painting a sunken region, the paint will flow to the edges rather than the recessed area. This is because the resistance to electrical forces is substantially higher within these zones than on all other surfaces [14]. As a result, the powder accumulates along their edges but considerably less inside, as illustrated in Figure 4. [18] Solved this issue by providing sufficient velocity of air flow to transfer the powder inside the recess. Change the operating parameters such as; the voltage, the distance from the sprayer to the product. On other hand factors which must be checked to control the efficiency of the electrostatic painting process such as; Electrostatic Voltage, part temperature at the time of coating, gun-motion speed and stroke, environmental conditions in the coating room.

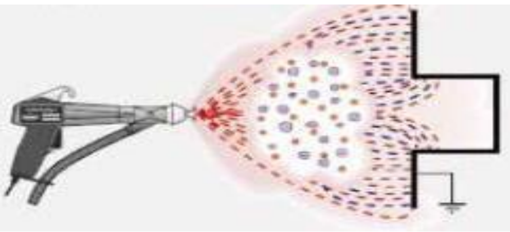


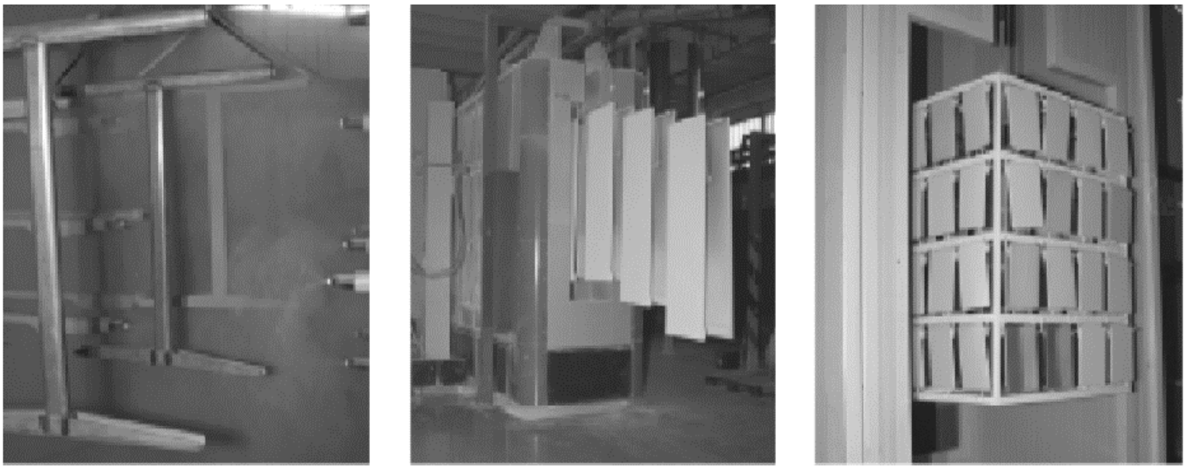
Fig. 4 Faraday cage effect [14]

C. Gun to target distance:

While carrying out electrostatic painting using spray gun, consider these important tips: If the gun and the part are too close together, they become electrically linked, providing a direct ground to the pistol. This has no effect on electrostatic transmission efficiency [14]. Furthermore, if the gun is too far away, the charged particles will seek for more nearby grounds.

D. The hunger fixture design:

Suitably built hangers are required for smooth conveyor operation and effective output. The appearance of the work piece hangers is determined by the application arrangement. A sufficient level of stability ensures problem-free coating and a fault-free production process. Because the hangers are partially electrostatically coated, circular material is preferred. Two complete sets of hangers are necessary to coat rationally: If the coating on one set of hangers is too thick, the second set should be used until the coating on the first set is removed. Figure 5 shows different types of parts hanged with different methods [14].



a) One side hang b) Two sides hang c) Four sides hang

Fig. 5 Hanging of objects [14]

E. Powder material:

When a powder is formulated to have high flow characteristics, it will be relatively easy to control thin film builds. Conversely, when a powder is formulated to have low flow characteristics, thick film builds will be relatively easy to control [13].

2.6 Taguchi method

Taguchi came to the conclusion that quality will be accomplished during the design stage before production. The Taguchi method's major goal is to minimize the state of variability around the target value of the process or product attributes. To accomplish this, the controllable elements that create this variability must be discovered, and the product and manufacturing process must be built with these factors in mind [19]. Taguchi's strategy is a systematic application of experimental design and analysis to develop product and process quality.

To establish the ideal process design, this technique employs experimental minimization of an expected loss function [20]. The Taguchi Method is an effective technique for improving the performance of products or processes [21]. Reduce variation by using statistical experimental design in a systematic manner. Experimental design is a critical strategy for product manufacturing and longevity [22]. Taguchi streamlined the use of orthogonal arrays in experimental design. Taguchi advocated using the signal-to-noise ratio (S/N) to assess the influence of factors on performance attributes [23].

3. Data collection and analysis

The data collection is started in an Egyptian factory for ceiling fan production. The factory produces 3000 fan/day; the company has many defective products due to presence of variation in blade weight. The presence of variation in weight causes unbalanced rotation of the ceiling fan, which is can lead to the many problems such as; vibration, or noise in the final product. The production line consists of seven processes; inspection, punching, treatment, electrostatic painting, curing, sorting, and packing as shown in figure 6. The basic steps in the production line are punching and electrostatic painting. The aim of this work is to collect data from the processes in the production line and analyzed them to achieve the sources of variation and finally try to eliminate or reduce them.

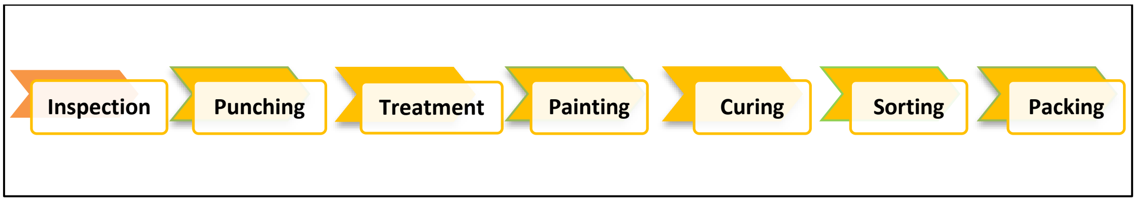


Fig. 6 The production line processes

The process begins with inspection of raw material by the quality control department. Once it is accepted, it is transported for cleaning from dust. After cleaning of the raw material, the metal sheet is forged into the die to take the shape of the blade through stamps by punching machine. The punching machine contains four stamps A, B, C, and D designed for producing four blades per stroke as shown in figure 7. The data collection process starts with preparing number of random samples from each stamp of the punching machine production, and then measures its weight. The sample size was fifty fan blades. The sample size had been calculated according to the military standard (MIL-STD-105D) and prepared to weight as shown in table 1.

Fig. 7 Punching Machine

Table 1 Weight of blades in (gram) after punching process

Sample No.	Blade Weight	Sample No.	Blade Weight	Sample No.	Blade Weight	Sample No.	Blade Weight	Sample No.	Blade Weight
1	582.8	11	584.4	21	582.9	31	583.2	41	582.4
2	583.5	12	584.8	22	583.7	32	582.5	42	581.7
3	584.8	13	584.0	23	582.7	33	582.1	43	581.3
4	584.7	14	582.1	24	583.3	34	583	44	581.9
5	584.7	15	582.4	25	584.6	35	581.9	45	580.6
6	584.7	16	581.7	26	581.0	36	580.2	46	580.8
7	582.7	17	583.0	27	582.2	37	582.4	47	581.9
8	583.0	18	585.9	28	580.5	3.8	581.8	48	580.7
9	581.9	19	585.6	29	581.1	39	582	49	581.7
10	580.0	20	583.8	30	582.7	40	580.1	50	581.4

3.1 Data analysis by using histogram

Histogram is one of the seven quality control tools that show the relative frequency or occurrence of continuous data values, indicating the position of the most frequent occurred values and the distribution of the data. It shows whether, the operation is on a target value or not, the degree of data variance, and if the data meets specification. Figure 8 shows the most frequency appeared weights are from (582-584) gram, the mean value is 582.8 gram and the standard deviation is 1.545 gram. The value of standard deviation indicates how the data set values deviate from the mean value of the given data. The coefficient variance gives the standard deviation as a percentage of the mean of the data. The coefficient of variation (CV) is given in the following formula: $CV = (S / X) \times 100\%$, Where: S = the standard deviation, X = the sample mean.

CV = 0.2650 %. The values of standard deviation and the coefficient of variation for the blades weight after punching process are in normal variation.

3.2 Data analysis by using X-bar control chart

X-bar control chart, which is emphasis on the assignable causes of variability as they occur. The X-bar control charts are the most common and useful statistical analysis tools for process control.

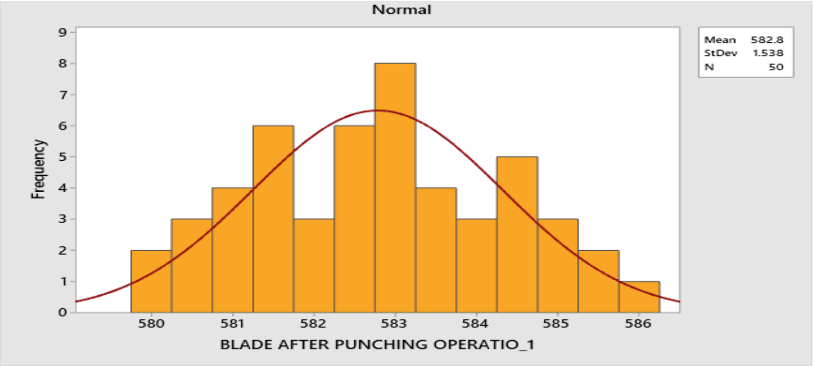


Fig. 8 Histogram of weight of blades after punching process

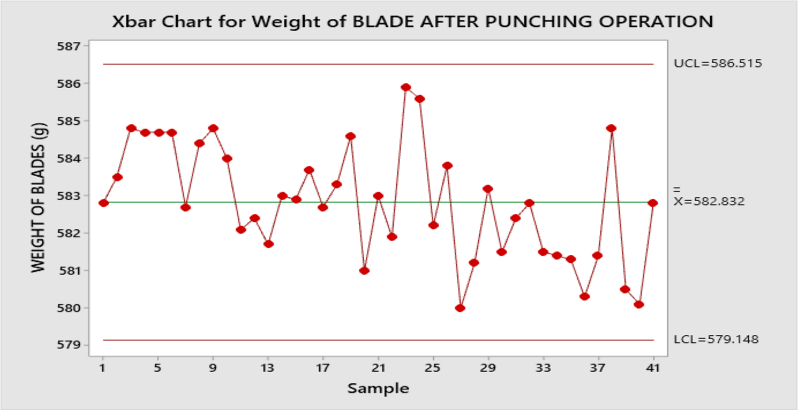


Fig. 9 X-bar control chart for blades after punching

Figure 9 shows that the mean control chart for blades weight after punching process has a normal behavior, the values are separated around the centerline of the control chart located in 582.8 g, and then it is assumed that the punching process does not inherit any assignable causes of variation and the process is statistically in control.

3.3 Electrostatic Painting Process

Electrostatic painting is the application of paint to blades using a magnetic field. It is based on the notion of opposites attracting. The attraction is created by applying a negative charge to the blades and a positive charge to the paint particles, resulting in a strong, smooth, good-finish paint that is plated on it. The procedure is divided into two parts: corona charging and turbocharging. A corona charged applicator is commonly referred to as a spray gun. Powder is delivered pneumatically to the spray gun through flexible tubing from a fluidized bed or vibrating hopper. The powders are sprayed from a spray gun and charged by the ions produced by a corona generated by an applied voltage on an electrode near the spray gun's outlet. The charged particles are then attracted and deposited on a grounded substrate. A negative voltage is frequently applied to the spray gun's electrode tip in order to generate a negative corona. As a result, the positive terminal is grounded to the substrate. Because a positively charged powder layer is more prone to electric breakdown, negatively charged particles tend to deposit more evenly. Figure 10 illustrates the factory's electrostatic painting plant.

Fig. 10 Electrostatic painting plant

3.4 Analysis of blade weight after painting

Table 2 represents the weight of blades in (grams) after electrostatic painting process for the same sample size. The Histogram in figure 11 shows the spread of the weigh after painting around the mean most frequency appeared weights are from 599-615, the mean value is 612.3 and the standard deviation is 17.04, The value of standard deviation indicates how the data set values deviate from the data set mean. The coefficient of variation CV= 2.78%. By comparing the variation of weight before and after punching process, it can be easily observed the large separation of data around the mean. The standard deviation doubled eleven times and the CV by ten times.

Table 2 Weight of blades in (gram) after electrostatic painting process

Sample No.	Blade Weight	Sample No.	Blade Weight	Sample No.	Blade Weight	Sample No.	Blade Weight	Sample No.	Blade Weight
1	657.8	11	604.3	21	599.6	31	590.3	41	661.6
2	610.6	12	630.3	22	609.0	32	616.8	42	604.0
3	625.0	13	606.4	23	615.5	33	617.0	43	588.4
4	607.4	14	632.8	24	610.5	34	607.0	44	604.0
5	599.0	15	607.0	25	610.3	35	605.0	45	603.5
6	651.6	16	598.5	26	609.8	36	603.6	46	600.3
7	610.3	17	597.5	27	606.1	37	608.6	47	602.5
8	641.6	18	588.8	28	607.0	3.8	604.0	48	610.5

9	601.0	19	658.4	29	633.9	39	605.7	49	604.0
10	60.5.6	20	616.1	30	619.5	40	606.0	50	603.3

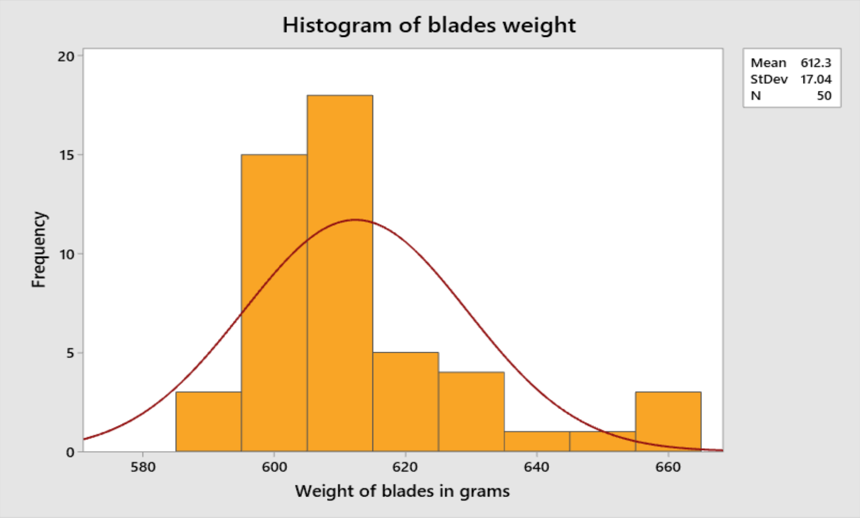


Fig. 11 Histogram of blades weight after painting process

3.5 Control charts analysis of blades weight after painting

The mean control chart of the blades weight painting process has an abnormal behavior. The values of points 1, 19 and 41 are out the upper control limit as shown in figure 12. Then the electrostatic painting process is considered to be out of statistical control and the main source of variation of blades weight. As the variability in weight of blades, result after painting process, so it is important to control the new intervene that causes this variability, which is the paint film thickness.

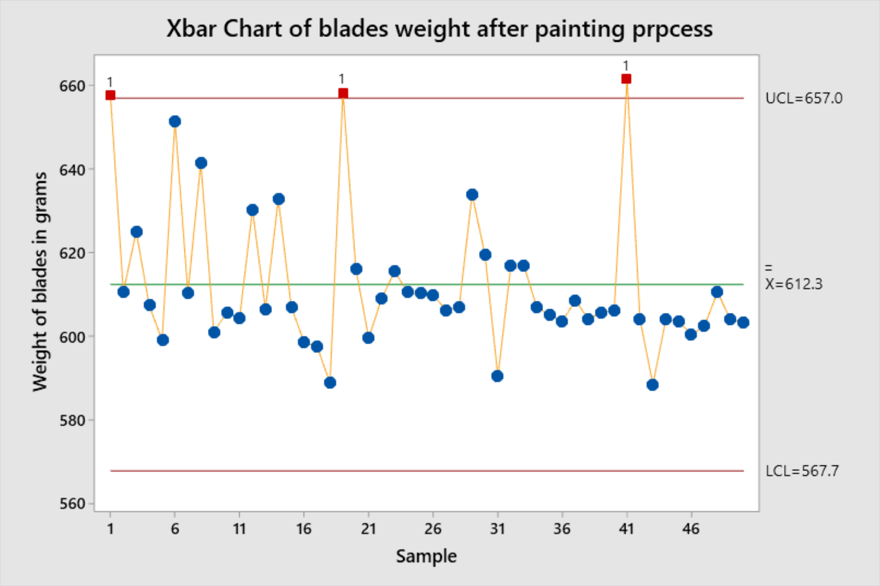


Fig. 12 The mean chart for blades weight after painting process

3.6 Coating film thickness analysis

The coating weight can be calculated from thickness through following equations:

- Calculate Paint volume (V = Paint thickness × Surface Area).
- Calculate Paint weight (W = Powder density × Paint Volume).

The target thickness of coating film is 60 μm. The calculated powder coating thicknesses for the same sample size after painting process are presented in table 3

Table 3 Powder coating film thickness after painting process in (μm)

Specimen No.	Thickness of coating	Specimen No.	Thickness of coating	Specimen No.	Thickness of coating	Specimen No.	Thickness of coating	Specimen No.	Thickness of coating
1	87.8	11	61.9	21	82.3	31	108.0	41	75.2
2	97.6	12	60.2	22	81.7	32	105.0	42	60.6
3	86.5	13	58.4	23	68.3	33	84.0	43	63.5
4	75.6	14	93.7	24	68.4	34	79.7	44	63.1
5	79.4	15	89.6	25	67.3	35	77.4	45	76.6
6	116	16	155	26	74.8	36	80.2	46	74.3
7	122	17	118	27	73.1	37	75.6	47	78.9
8	95.5	18	101	28	81	3.8	70.6	48	95.9
9	91.2	19	106	29	97.6	39	76.9	49	80.1
10	99.6	20	103	30	86.5	40	88.7	50	83.7

The mean control chart for coating thickness showed an abnormal behavior and variation in the thickness of the blades. The center line located at 86.5 μm, and the standard deviation is 19.41. The coefficient of variation CV= 22.4%. The points 7, 17, and 30 are out the upper control limit shown in figure 13. Then the electrostatic painting process is considered out of statistical control and inherits large variability.

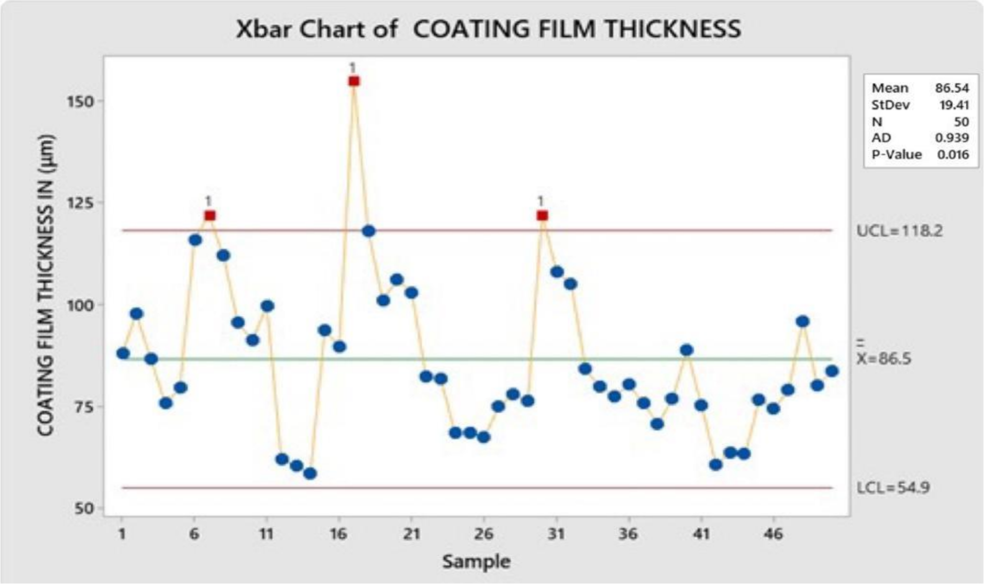


Fig. 13 The mean chart for coating film thickness

3.7 Capability analysis of the process

The capability of the process is defined as the scientific process analysis to define its behavior. The indices of the process capability measure the potential of the process to satisfy the required specifications of product quality. Analysis of process capability is an important part for sustainable quality program. The process capability indices (C_p) compare the specification variations with the actual variation amplitude of the process. It can be calculated by dividing the specification variations by the process variation. Where σ is the process standard deviation and (USL, LSL) is the maximum and minimum specification limits of the product quality. Table 4 defines the categories of the capability indices on any process.

$$C_p = \frac{USL - LSL}{6\,\sigma}$$

Table 4 categories of the capability indices on any process

Capability index values	Class	Recommendation
$C_p = 2.20$	World class	Six sigma quality
$C_p > 1.330$	Class 1	Suitable
$1.0 < C_p > 1.330$	Class 2	Acceptable, need tight
$0.67 < C_p < 1.0$	Class 3	Required significant
$C_p < 0.67$	Class 4	Not acceptable

The analysis of process performance indices (C_{PK}) is the capability measures commonly used in most industries because it indicates whether, it is capable and how well-centered the process is. The C_{PK} is a perfect indicator of how far the process operates from the center as shown in figure 14. It is computed from the following formula:

$$C_{pk} = \text{Min}\left[(\mu - LSL) / 3\sigma\ ,\ (USL - \mu) / 3\sigma\right]$$

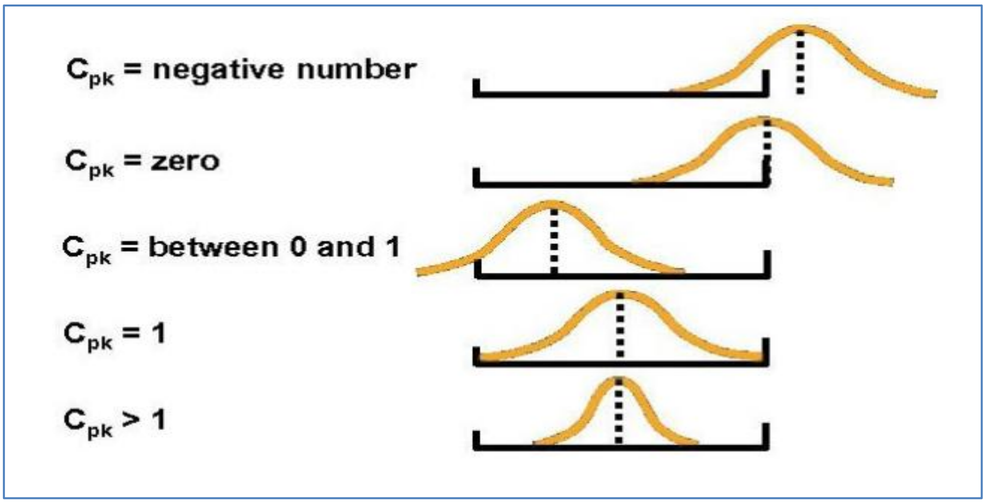


Fig. 14 Process performance indices analysis

3.8 Normality test analysis

Process capability analysis need to show the data fits as a normal distribution. The equation of process performance is used when the process of electrostatic painting is followed a normal distribution. The statistical Anderson-Darling test is given in the following formulation:

$$A^2\text{Critico} = -N - S$$

$$S = \sum_{i=1}^{N}\left(\frac{2i-1}{N}\right)\left[\left(\ln F\left(Yi\right)\right)+\ln\left(1-F\left(Y_{N+1-i}\right)\right)\right]$$

Where:

N	the data total.
S	the statistical for Anderson-Darling.
i	the number of observations.
$F(y_i)$	the normal accumulated distribution of probability with a given mean and variance from the sample arranged from the lowest to the highest value.
$F(Y_{N+1-i})$	is the normal accumulated distribution of probability with a given mean and variance from the sample arranged from the lowest to the highest value.

The data are fitted to the line representing the normal distribution as shown in Figure 15. Furthermore, the calculated p-value for the test is higher than the value of 0.005 therefore; the null hypothesis is accepted and ensures that the data are fit into normal distribution.

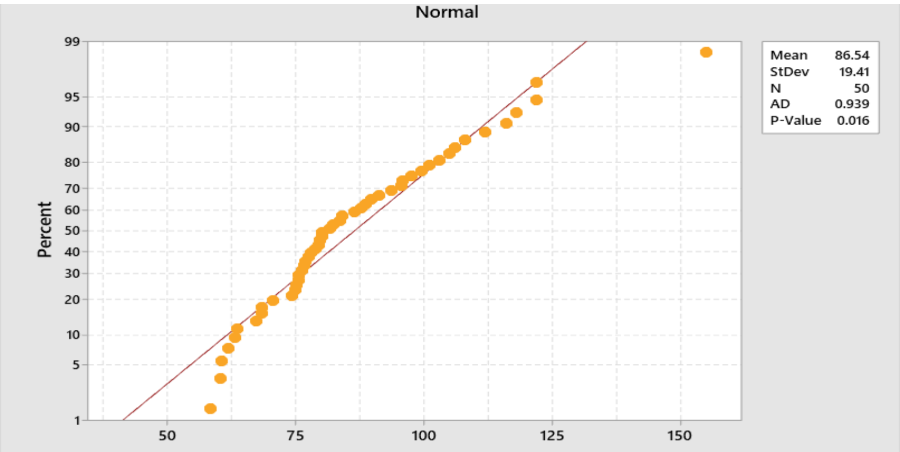


Fig. 15 Probability plot of coting film thickness

3.9 Process capability analysis after painting

Fifty random samples are withdrawn and analyzed to show the behavior of the electrostatic painting process. The specifications limits for the thickness of coating film are lying between (50 and 80) µm and the target is 60 µm. The process is out of control (Cp = 0.47). Significant improvements are needed to achieve the traget requirements. In addition, the calculated value of process performance indices (Cpk= - 0.21), ensure that the process is not located on the target as presented in figure 16. The achieved results showed that the process of electrostatic painting is fails to meet specifications. Then it is important to illustrate the potential causes of the painting variability to bring the process close to company specifications.

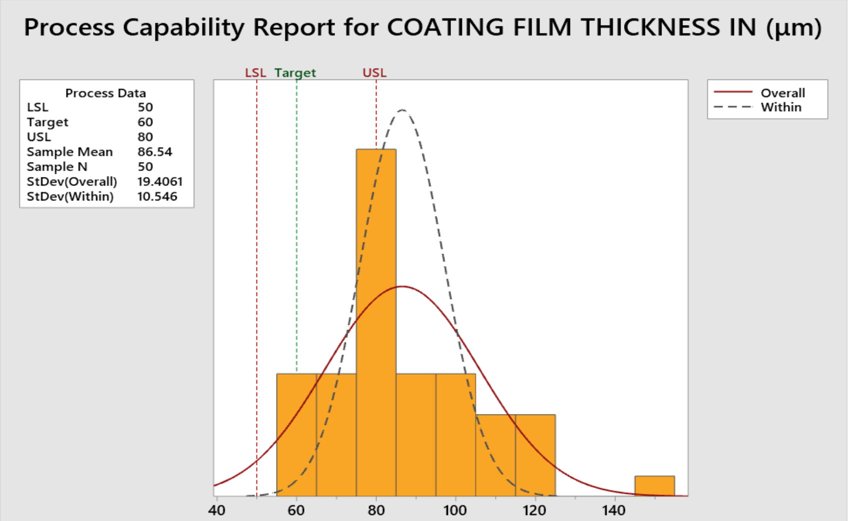


Fig. 16 Process capability analysis results

3.10 Cause and effect diagram analysis

The main causes of variability in the coating thickness of the van blades are analyzed by the cause and effect diagram as illustrated in figure 17. These causes are identified by literature survey of common factors affect the process, brainstorming with the quality control department, direct observations of the mistakes happened during the process, and then these causes are summarized in a fishbone diagram.

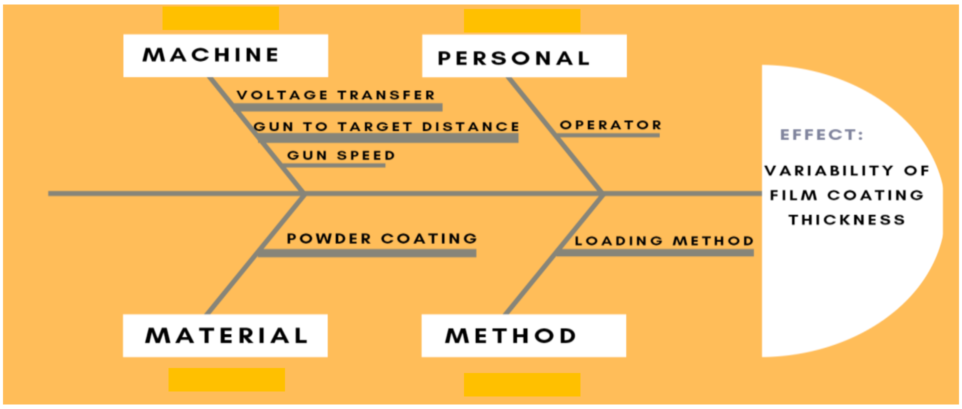
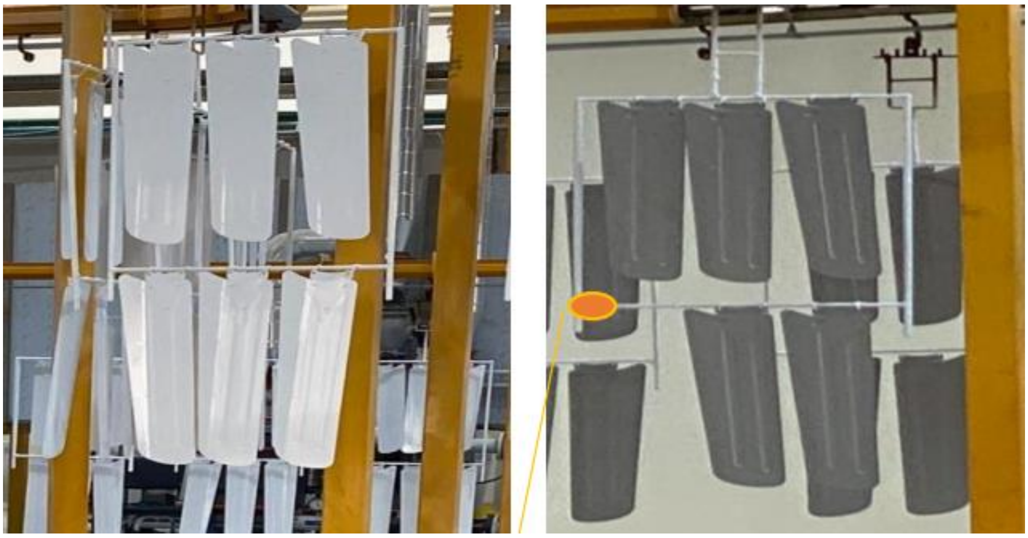


Fig. 17 Fishbone diagram of the variability of film coating thickness

The data analysis from the fishbone diagram is concluded in some critical factors affecting the variability of film coating thickness such as;

- The loading method of the fan blades, it is a critical factor that can affect the distribution of powder on blades. The carrier of blade contains two levels and each level contains three blades hanged through fixed hook as shown in figure 18 a. It is observed that the hook of blade frequently got fractures. Then the production hangs only five or four blades on the hooks as shown in figure 18 b. The result is uneven distribution in powder quantity between blades.

- Powder coating materials, the powder material considered as an important factor that affects the thickness of coating and distribution of powder. Typically (10 - 17) % of blades repainted due to defects such as low film thickness, which produce uneven distribution of powder along the film thickness. Through the self-limiting mechanism, the particle size determines the potential film thickness in the electrostatic spray process. Thick film builds are produced by a coarse size distribution, while thin film builds are produced by a narrow size distribution. The transfer efficiency may be a valuable reference when choosing on a powder composition and particle size.
- Operating parameters of the electrostatic machine, Statistical analysis tools can be helpful when considering the effect of multiple factors of machine parameters on particular outcomes. The Taguchi technique has established itself as an important tool for robust design in achieving high quality processes and products that are least sensitive to noise while incurring the lowest production costs. The Taguchi experimental design and analysis to determine the best combinations of process parameters entails the procedures outlined below as shown in figure 19.



a) Free of defects carrier b) Broken hook carrier

Fig. 18 Loading method of the fan blades

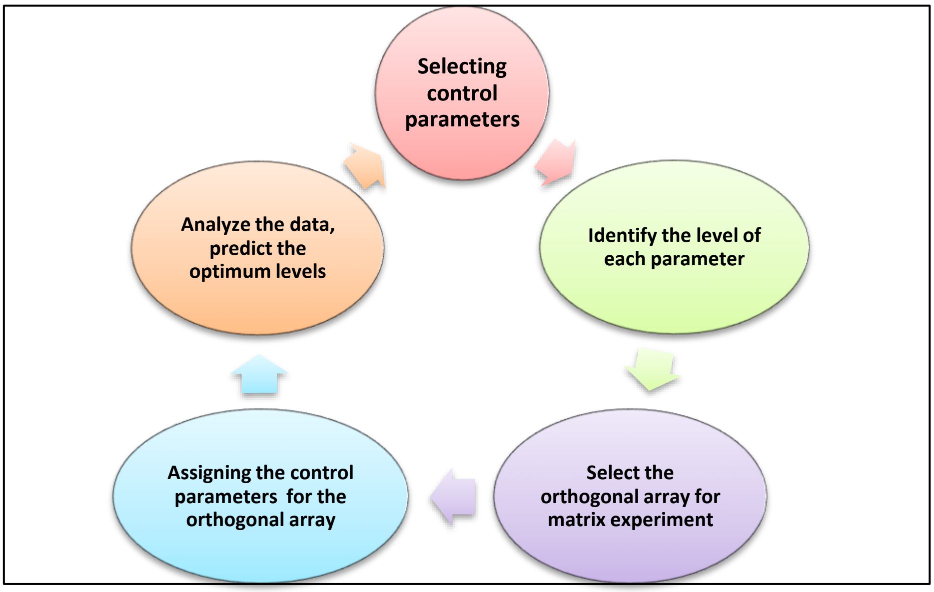


Fig. 19 Steps for Taguchi Method

4. Implementation of solution

The analysis of data in the ceiling fane production line reveals that the main source of variation lies in the process of electrostatic powder coating. The achieved results showed that the main causes of variation are related to three issues; loading method, powder material, and the operating parameters of the electrostatic machine. The loading method is solved by proper and periodic maintenance operation to the loading system components. The powder material is solved by proper choice of the particles size of the material of powder according to the world specification. The third and the essential cause is the operating parameters of the machine. Taguchi method is used to select the operating parameters to optimize the process and reduce the variation in the powder coating process as shown in figure 19.

4.1 Controlled parameters selection

It is crucial to select the variables that are most likely to have an impact on the quality characteristic that has to be enhanced while getting ready for a Taguchi method experiment. During the experiment, the controlled parameters are identified and managed. The selection of four process parameters is depicted in figure 20. Table 5 displays the values of the current process parameters.

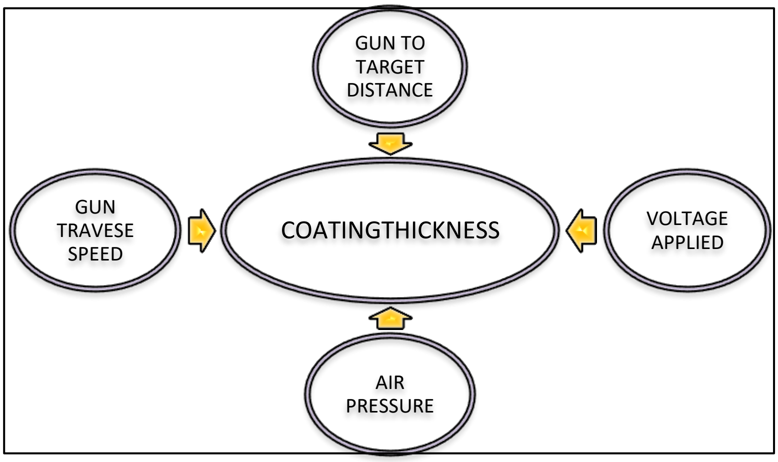


Fig. 20 The selected operating parameters of the process

Table 5 Current values of the process operating parameters

Parameter	Voltage (kV)	Gun Speed (mm/ s)	Gun stand-off Distance (mm)	Air Pressure (bar)
Value	85	25	190	3.5

4.2 Response Quality Characteristic

The aim of this work is to minimize the variability in blades manufacturing, therefore the response characteristic will set to be the standard deviation of coating thickness. The standard deviation is the variation in response caused by the presence of noise. It is the difference in reaction when the same control factor settings are used at different times in an experiment. It is the mathematical distance between the response and the mean value of the response. Taguchi design focuses on decreasing the standard deviation to reduce variance and develop a design that can provide a nearly constant response for any noise factor number.

4.3 Levels of parameters

Each parameter level has a different value, which will be explored throughout the trial to observe how these variables relate with one another and affects the answer. The number of levels is determined by the process's conduct and the fluency of available trails. There should be three minimal levels of process parameters to accurately depict the behavior of the study's output variables as presented in table 6.

Table 6 Levels of process parameters

Process Parameters	**Levels**		
	Level 1	**Level 2**	**Level 3**
Input Voltage (kV)	80.0	90.0	100.0
Gun speed (mm/s)	25.0	35.0	45.0
Gun stand-off distance (mm)	200	300	400
Air Pressure (bar)	2.50	3.50	4.50

4.4 Orthogonal Array

Orthogonal arrays are the bare minimum of experiments that depict the numerous factor combinations. The output of the orthogonal arrays is optimized in terms of the signal to noise ratio (S/N) of the responses, which decreases process variability. The Taguchi orthogonal array has three tiers of four parameters. with the help of software Minitab 19 as shown in table 7. The proposed experiment table obtained from the experimentation as shown in table 8. The goal of the experiment is to develop a control factor combination that minimizes variance in response caused by noise components by minimizing the S/N ratio and the standard deviation. The S/N ratio is simply the ratio of the signal factor to the noise factor in the experiment. S/N ratio can be maximized, lowered, or kept at nominal value depending on the optimization target. It aids in selecting control settings that can mitigate for noise impacts to the greatest extent possible. The S/N ratio was kept to a minimum in this study since the purpose of the design is to set the standard deviation of thickness to limit the effect of noise effects on the response.

Table 7 Taguchi experimental design summary

Taguchi orthogonal array	L9(3^4)
Factors	4
Runs	9

Table 8 Proposed orthogonal array (L9) Taguchi method

	Parameters			
Trail NO	Applied voltage (kV)	Gun speed (mm/s)	Standoff distance (mm)	Air pressure (bar)
1	80.0	25.0	200	2.50
2	80.0	35.0	300	3.50
3	80.0	45.0	400	4.50
4	90.0	25.0	300	4.50
5	90.0	35.0	400	2.50

6	90.0	45.0	200	3.50
7	100.0	25.0	400	3.50
8	100.0	35.0	200	4.50
9	100.0	45.0	300	2.50

For the experiment used for each condition, forty samples are created, and table 9 shows the thickness of the coating film measurement results. As illustrated in table 8, the configuration producer changes the machine settings to the levels recommended by the Taguchi array guide, while keeping the other process variables constant. Figure 21 depicts the machine interface with the applied voltage and the desired pressure change. The gun speed and standoff distance are modified in Figure 22.

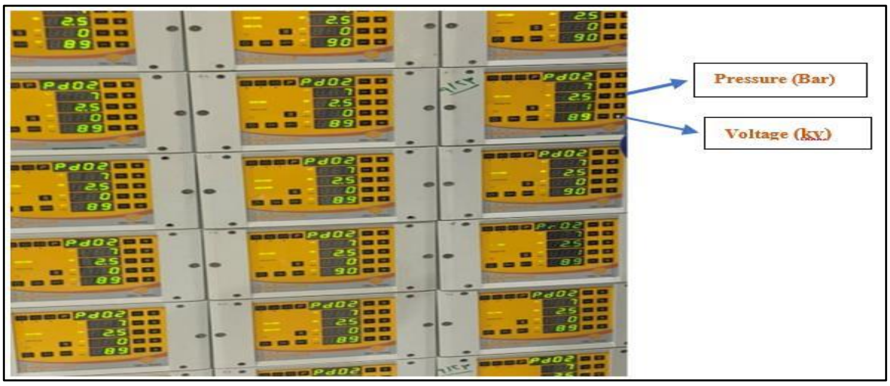


Fig. 21 The setup voltage and pressure

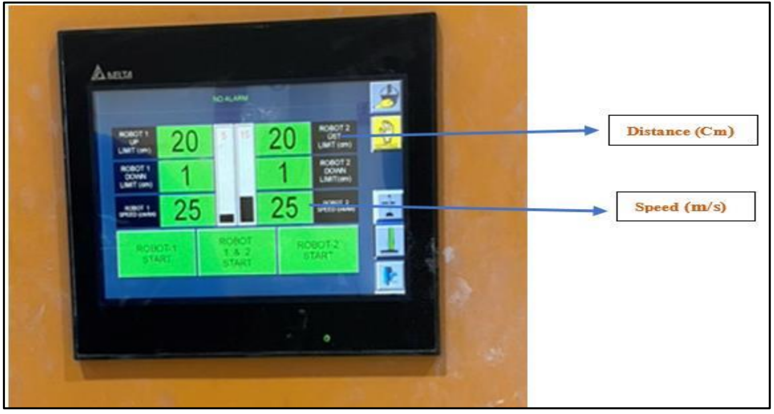


Fig. 22 The setup of the distance and speed

Table 9 Coating Film Thickness (μm)

Sample No	Trails No							
1	88	60	39	66	61	40	42	60	60
2	76	59	35	72	64	38	40	52	74
3	87	62	37	70	68	37	40	54	69
4	82	55	30	61	64	30	48	63	73
5	73	48	30	60	54	55	46	55	73
6	77	51	28	65	55	59	46	56	83
7	68	52	58	67	61	27	42	59	71
8	88	52	60	68	56	14	54	52	77

9	80	51	64	65	61	15	46	60	63
10	78	58	53	69	60	22	43	68	73
11	76	64	64	65	61	25	47	55	76
12	75	55	62	72	68	32	43	55	80
13	74	58	56	62	57	25	44	63	67
14	72	53	64	61	58	18	52	61	78
15	81	54	66	68	58	29	47	63	74
16	85	57	58	63	54	29	46	61	75
17	74	53	67	65	59	28	45	59	74
18	73	62	63	70	55	45	44	60	80
19	75	59	63	65	58	17	48	65	85
20	77	54	70	64	61	21	44	61	77
21	75	59	58	71	58	41	42	59	67
22	79	46	53	65	68	31	47	57	74
23	75	52	60	59	68	39	50	60	69
24	79	54	60	59	61	41	45	59	61
25	80	55	63	66	59	41	39	55	74
26	80	56	64	63	66	48	43	56	73
27	84	53	64	61	71	43	46	60	68
28	84	56	60	58	67	46	43	59	62
29	79	54	54	56	62	31	43	58	63
30	87	53	63	62	65	32	44	57	69
31	84	51	60	69	56	49	46	57	65
32	88	66	65	63	55	49	44	65	63
33	88	58	60	67	59	52	43	62	77
34	79	56	65	64	57	45	47	65	71
35	79	56	56	61	62	49	48	58	72
36	80	54	61	61	68	52	50	67	71
37	78	54	67	59	62	42	27	58	75
38	84	60	65	68	68	42	45	60	77
39	86	56	64	57	68	52	40	62	69
40	86	61	68	58	57	41	47	67	73

5. Results and discussion

5.1 New operation parameters results

The results of the new operation parameters revealed that each of the four components has three levels. As a consequence, L9 is the best orthogonal array for this research. This orthogonal array is comprised of nine experimental runs, each of which has forty random samples. The sample means of each treatment are used in the orthogonal array statistical analysis. Figure 23 displays the results of the experimental design.

Fig. 23 Main effects plots for coating thickness versus the operating parameters

Table 10 analyzes the relative magnitude of effects using delta statistics. Minitab assigns ranks based on highest delta values. The rankings indicate how important each aspect is to the response. Powder consumption rate has the biggest effect on the sample weight, followed by voltage, speed, distance, and pressure in that order, according to the ranks and delta values for various factors. according to previous research, the third level of input voltage (L3), set at 100 KV, the second level of gun speed (L2), set at 35 m/s, the second level of stand-off distance (L2), set at 300 mm, and the first level of air pressure (L1), set at 2.5 bar all improve the uniformity of coating thickness, as shown in table 11.

Table 10 the rank of data according to Delta

Level	Voltage (KV)	Gun speed (m/s)	Stand-off Distance (mm)	Air pressure (bar)
1	64.310	62.870	58.730	70.980
2	54.060	58.830	63.890	45.710
3	58.700	55.370	54.440	60.380
Delta	10.250	7.500	9.450	25.270
Rank	2	4	3	1

Table 11 Optimizing parameter values from Minitab.

Parameter	Value
Voltage (kv)	100
Gun Speed (m/s)	35
Distance (mm)	300
Pressure (bar)	2.5

5.2 Verifying the results of optimize parameters

Ten samples are selected to check to validity of the optimization parameters as presented in table 11. The achieves results showed that the blade coating thickness are decreased after setting the new parameters as shown in table 12 which ensure the effectiveness of the new parameters. The achieved results after using the selecting parameters ensure that the standard deviation is decreased from 7 to 3.68 µm with 52% improvement, as shown in figure 24.

Table 12 the blade coating thickness in (µm) after setting the new parameters

Sample No	Coating Thickness (µm)
1	63
2	64
3	60
4	72
5	62
6	65
7	68
8	63
9	66
10	60

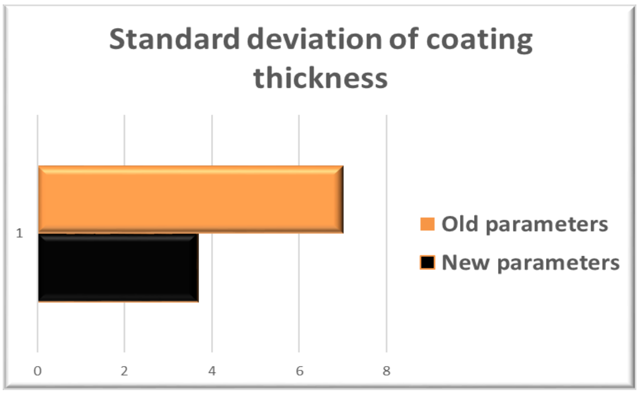


Fig. 24 Standard deviation of coating thickness before and after improvement

5.3 Process capability results

Under optimal operating conditions, a capability analysis of the electrostatic painting process was performed. Figure 25 depicts the findings of the process capability analysis. Forty samples from the electrostatic painting procedure are taken for the testing. According to the findings, the process's performance capability indices (C_{pk}) have grown from (-0.21 to 0.52). The indices of the process capability (C_p), which previously had a value of 0.4, have been raised to 1.38. The findings obtained show that the electrostatic painting procedure has been enhanced, has greater centering, and is able to match the necessary criteria.

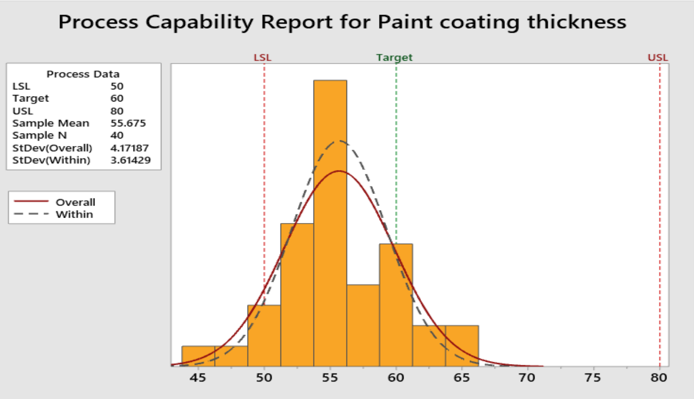


Fig. 25 Process capability after setting the new parameters

5.4 Powder consumption results

Powder consumption during the painting process is a very important factor and should be evaluated because it directly affects the cost of the process. Before setting the new parameters and improper use the operating conditions of the painting machine, the result is increasing powder consumption and consequently increasing the total cost. The consumption of the powder is calculated before and after the setting of new parameters for a given samples as shown in Table 13. The average powder consumption before after setting the new parameters are calculated around (24 and 13) g/blade respectively. Figure 26 show the comparison between the average powder consumption before and after setting the new parameters.

Table 13 Powder consumption before and after using the new parameters

	Before using the new parameters		After using the new parameters	
Sample No	Coating thickness (µm)	Powder consumption (g/blade)	Coating thickness (µm)	Powder consumption (g/blade)
1	87.8	21.915	60	14.976
2	97.6	24.361	59	14.726
3	86.5	21.590	62	15.475
4	75.6	18.870	55	13.728
5	79.4	19.818	48	11.981
6	116	28.954	51	12.730
7	122	30.451	52	12.979
8	112	27.955	52	12.979
9	95.5	23.837	51	12.730
10	91.2	22.764	58	14.477
11	99.6	24.860	64	15.974
Average		24	Average	13

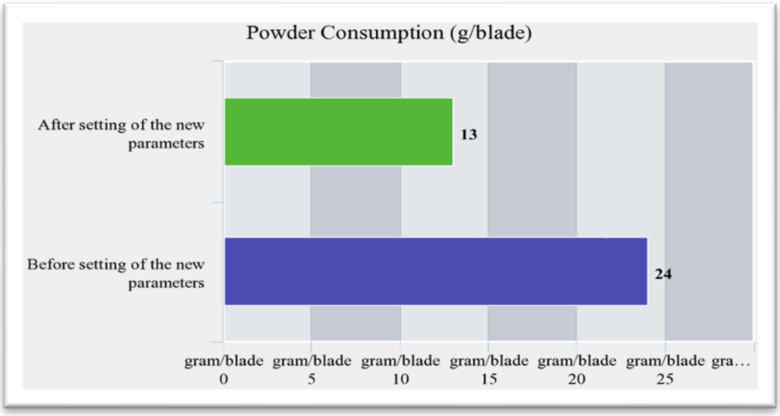


Fig. 26 Powder consumption before and after setting the new parameters

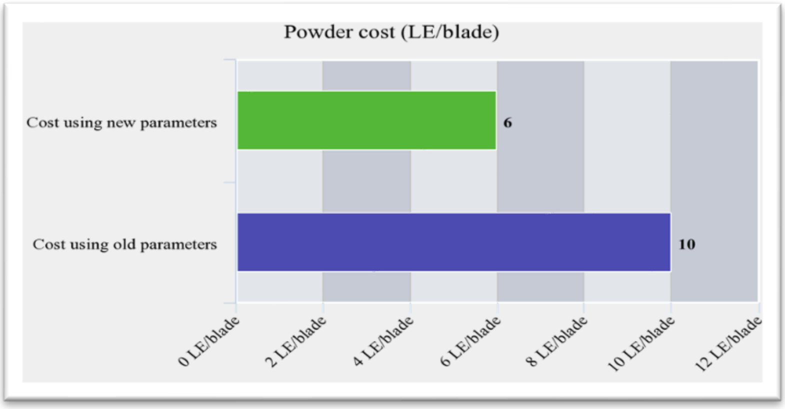
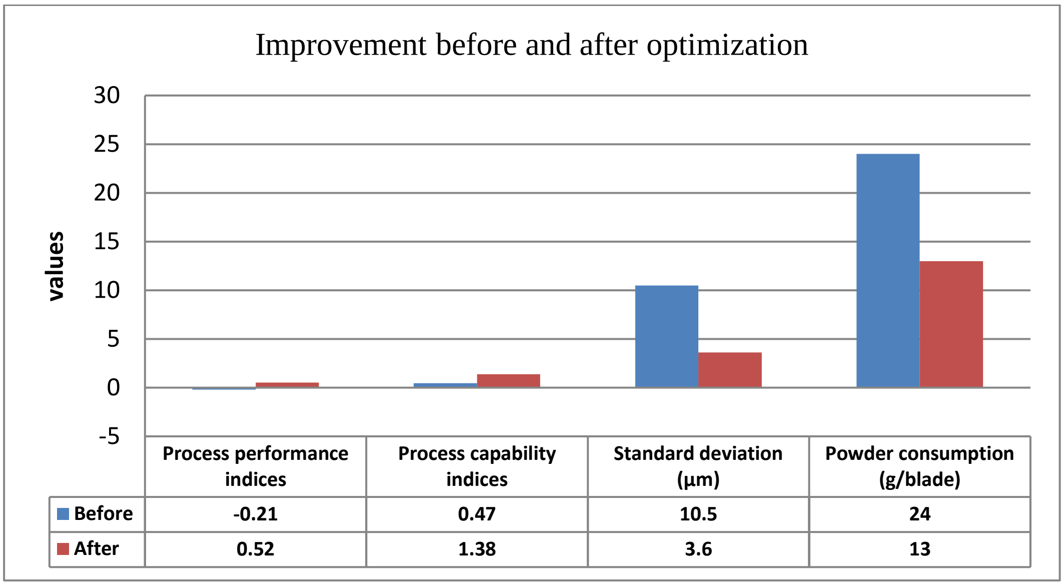


Fig. 27 Cost of blades painting before and after setting of the new parameters

The achieved results showed that a significant reduction in powder consumption by 46% after setting the new parameters as shown figure 26. According to the company data the cost has significant decrease from (10 to 6) LE/ blade with total cost reduction by 40% as shown figure 27. The value of process performance indices is improved from (-0.21 to 0.52), the value of the process capability indices is increased from (0.47 to 1.38), the powder consumption is reduced from (24 to 13) g/blade, and the standard deviation is decreased from (10.5 to 3.6) as shown in table 14. The comparisons between the improvement before and after implementing the optimization parameters for electrostatic painting process are shown in figure 28. The improvement results in a significant decrease in total cost of blade paint from (10 to 6) LE/ blade with total saving 12000 LE/day, and 3,456,000 LE/year as shown in table15.

Table 14 The obtained results before and after optimizing the parameters

Assessment criteria	Implementation of optimization parameters	
	Before	After
Process performance indices	-0.21	0.52
Process capability indices	0.47	1.38
Standard deviation (μm)	10.5	3.6
Powder consumption (g/blade)	24	13



	Process performance indices	Process capability indices	Standard deviation (µm)	Powder consumption (g/blade)
🟦 Before	-0.21	0.47	10.5	24
🟥 After	0.52	1.38	3.6	13

Fig. 28 The improvement before and after optimization the parameters

Table15 The cost saving from improve the operating parameters

Assessment criteria	Before improve	After improve	Total saving
Powder consumption (g./Blade)	24	13	11
Cost of blade painting (LE/Blade)	10	6	4
Production (Blade/day)	3000	3000	
Total saving (LE/ Month)	4x24x3000		288,000
Total saving (LE/ Year)	12x288,000		3,456,000

Conclusion

A company that can please its customers by enhancing and regulating quality can outperform its competition. Statistical quality control is critical for assessing process variation and optimizing process performance. This paper is considered a research methodology with a case-based analysis and optimizes the operational parameters of the electrostatic painting process to reduce the variability in fan blades painting process. An experimental investigation for optimized operational parameters of electrostatic painting process was conducted by using Taguchi design method and Minitab 19 software. This work adopted in an Egyptian factory for producing ceiling fane especially in the fan blades production line. The obtained results from data analysis reveal that presence of variation in the blades weight in electrostatic painting process. The variation is evaluated through statistic tool such as; the standard deviation, control charts, and process capability analysis. Experimental design is carried out using Taguchi method which focuses on the attention of the improvement of the critical process parameters and finds better combination of machine parameters to reduce the variability in response quality characteristic. The obtained results showed that the best operation parameters of the electrostatic painting machine: 100 KV, 2.5 bar pressure, 35 m/s speed, and 300 mm distance. The results showed that the process performance indices improved, the value of process capability indices is improved from class 4 (not acceptable) to class 2 (acceptable), the powder consumption is reduced by 46 %. The total cost of blade paint decreased by 40 %, with total saving 3,456,000 LE/year.

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