Reduction In Flow Marks On Molded Plastic Parts By Applying Six Sigma

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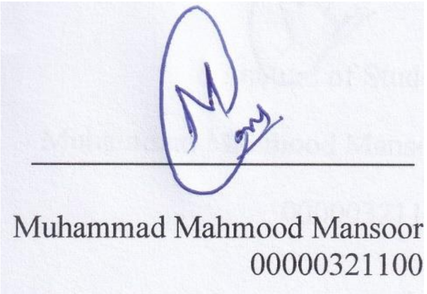

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DEDICATION

This thesis is dedicated to my beloved parents and my endeared sibling with whose unsurpassed support, encouragement and love have made this wonderful accomplishment possible.

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ABSTRACT

This research work is conducted to reduce the current cost of poor quality of water dispenser. Since this product is facing very low overall gross profit, there is a need to work on the quality issues being faced by the team. Among these quality issues, one of the major impacts was due to expensive rework being done to hide the appearance of flow marks after paint application. A Six Sigma Study was planned for this research and DMAIC methodology was used to solve this issue. After a detailed analysis of the problem, a DOE was proposed, and experiments were done to get the optimized parameters for painting process. The results were verified and applied systematically after approval from all stakeholders. The rework was reduced from 95% to less than 5% thus bringing significant saving in cost

Key words: Six Sigma, DOE, DMAIC, Flow Marks

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CHAPTER 1
INTRODUCTION

To remain the number one choice for customers, making the business more competitive is the need of time where core focus must be on minimum input and maximum output without compromising the quality of product [1]. From several factors which contribute to business success, cost saving is one of the major goals which must be achieved through process optimization as well as applying lean methodologies used for improvement [2]. To achieve maximum cost saving, management should be vigilant on the cost of quality and cost of poor quality incurred in the process [3]. Lean management tools can be handy for reducing the cost of poor quality like six sigma methodologies [4].

Total cost of quality is the finances utilized in maintaining the quality standard and prevent poor quality [5]. It can be in the form of scrap, rework, repair, and warranty failure. There are two types of Cost of Quality named as Cost of Good Quality (COGQ) (Appraisal cost + Prevention Cost) and Cost of Poor Quality (COPQ) (Internal + External failures cost) as shown in Fig 1.1 [6]. Each type is further categorized into unavoidable and avoidable costs as referred in Fig 1.1. Some portion of COPQ is unavoidable and incorporated in process as limitations that no matter how efficient our process is, a particular amount of cost will be lost [7]. Hence, goal must be to minimize the unavoidable part and eliminate the avoidable part.

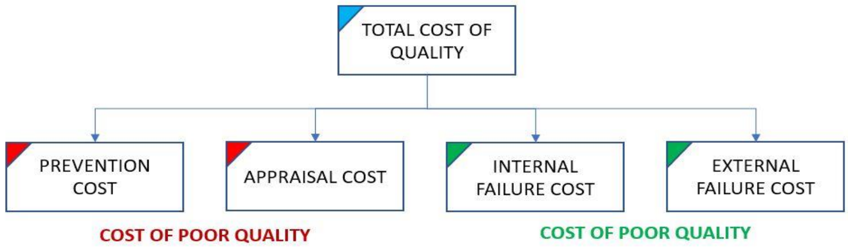

Figure 1.1 Total Cost of Quality [69]

Internal COPQ is mainly comprised of waste, scrap, rework, and failure analysis while External COPQ has expenditures on repairs and servicing, warranty claims, complaints and returns [8]. Companies must have a proactive approach in managing the cost of quality and carefully invest in prevention and appraisal costs so that exposure to both internal failure and external failure costs is reduced [9]. In this thesis, we will be focusing on reducing the Internal Cost of Poor Quality by using lean manufacturing tools.

1.1 BACKGROUND

To compete and be amongst the top tier manufacturing firms, it is important that the cost incurred to produce a quality product must be minimal where quality of product is not compromised [10]. It is not just cost saving but focusing on implementation of continuous improvement processes so that the cost reduction is not bound to just some numerical targets [11]. Reduction in COPQ does not only benefit in terms of capital but also results in reduced lead times as well as customer satisfaction and trust [12].

1.1.1 INTRODUCTION TO SIX SIGMA

Six Sigma was introduced by Motorola as a rigorous statistical tool for controlling the quality of a process and further developed by General Electric [13]. It targets to reduce the defects to 3.4 in a million opportunities [14]. Six Sigma is a process improvement methodology which ensures that the process is well in control and lies between the limits defined by the customer [15]. By applying this methodology on any problem, the current process variations are measured, and the critical variables are worked upon the reduce the process variations and limit them between the limits defined by the customer.

1.1.1.1 SIGNIFICANCE

Without considering the organization’s industry or size, this methodology provides us a standard approach to problem solving technique and a model to be used along with its numerous tools for bringing a process on paper and analyzing it from each aspect for further improvements [16]. For problem solving, DMAIC methodology is used by most of the industries around the world which is explained step by step [17].

1.1.1.2 DEFINE

This phase provides a problem statement which explains the issue being faced and the current and expected targeted values which will be achieved by completing the entire study. It is followed by a business project charter which clarifies the main stakeholder and the timelines for major tasks. It defines the in scope and out of scope areas of the study being carried out. Voice of Customer (VOC) is shown and the Critical to Quality drivers along with their specifications are drawn from the VOC [18]. The related business opportunities are specified, and the list of processes are shown through a process map. A complete define phase will help to give a clear picture of the objectives and timeline for project completion.

1.1.1.3 MEASURE

Measure phase helps to bring down in the form of tabular values or graphs about the current process performance and shows the gap between the target and current performance. Without having a clear benchmark, it is difficult to keep a track of process improvement which will be carried out in the later stages. In this phase we develop a data collection plan which includes the instrument to be used, the authenticity of the data collector and the instrument and the data collection criteria. A failure mode and effect analysis (FMEA) is carried out to highlight the ways in which the process can fail as well as the reasons for failure ending up recommending improvements to reduce the risk of that failure. The use of visual tools like control charts, bar charts, pareto charts etc. can help to give a better understanding of the current process [19]. Major part of our study will be Design of Experiments (DOE). Design of Experiments (DOE) deals with planning, conducting, analyzing and interpreting the results to evaluate the values which control the results. DOE is a powerful tool for cases where there are multiple input variables and there is a need to find the correlation between these variables and their effect on the output variable [20].

Factors are the input variables which are selected to manipulate in experiments while the Levels are the specific values of our input variables which we want to set. Normally we have two or three levels to ensure our working is simpler as increasing the levels will make it more complex. There are 3 main types of DOEs.

1. Full fractional designs
2. Fractional factorial designs

3. Response surface designs

Full factorial designs contain all possible combinations of the factors under consideration. Fractional factorial design consists of a fraction of runs for experiments. Although it uses resources efficiently, but it comes up with a tradeoff in information. Response surface methodology includes the optimization of factor variables to a desired minimum or maximum output [21].

When set of factors and levels are determined for any experiment, combinations for trials are made using Taguchi's Orthogonal array. Taguchi's OA allows us to consider combination of factors at different levels. It ensures that all factors at all levels are considered in preparing the data set. The number of combinations/runs is determined by the formula:

$$Experimental\ runs = Level^{Factor}$$

1.1.1.4 ANALYSE

This phase helps us to find out the underlying causes of the problem to ensure that actions taken are coming right from the roots of problem. Critical steps at this stage are root cause analysis (RCA) using either a fishbone diagram or any other related tool followed by a priority matrix to prioritize the noise, procedural and controllable causes. FMEA can be done in ANALYSIS phase instead of MEASURE phase to related more to the RCA. Visual representations like multi-vari charts are used to analyze the data gathered from the measure phase [22]. Finally, a plan for improvement is developed with a list of activities listed which must be considered to achieve the desired results or come near to the target.

1.1.1.5 IMPROVE

Improve phase is the brainstorming of all the available ideas where Design of Experiments (DOE) is carried out to find the most suitable actions needed to achieve the targeted in the project charter. The activities are implemented, and a test is carried out to verify the results. Process map is revised accordingly. All stakeholders are informed about the changes made. Use of improvement management software can be useful at this part of study [23]. It helps in easier tracking of projects and improving cross functional collaboration of teams.

1.1.1.6 CONTROL

After all the changes are in place and the test results are verified which are successfully catering all the problems addressed in the project charter, there arises need of putting the process under strict control to ensure its sustenance and long-term effectiveness. Here new work standards are identified and documented accordingly after agreement from all stakeholders. A quality control plan is developed to ensure that the entire team is working on same metrices. Statistical Process Control is used to monitor the actions executed and to identify any issues that arise [24]. Additional improvements are determined if any figured out.

1.1.2 COST OF POOR QUALITY

Cost of Poor Quality refers to the direct and indirect cost associated with defects generated in a process. This cost is variable and depends on how far the defect is detected. This cost can be calculated by adding the cost of resources used to kill the defect and the cost of impact on the main process [25]. Usually when error is detected at an early stage, the cost incurred is lower as compared to errors detected at later stages as the repair does not involve much disassembly. As the process extends, the cost of part increases as well as does the cost of poor quality at any point further [26]. The levels of cost and coordination usually increase gently but as soon as the product reaches the customer, the repair costs shoot sharply as seen in Fig 1.2.

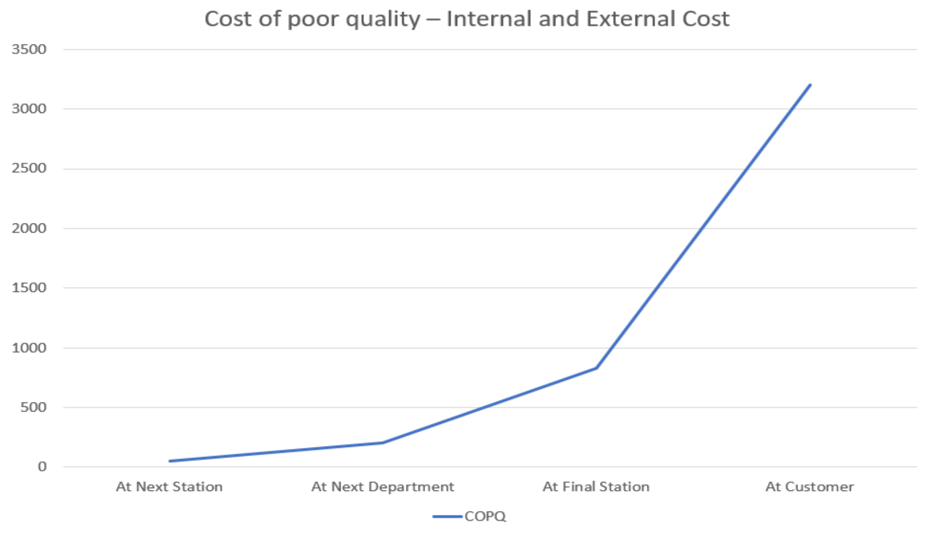

Figure 1.2 Cost vs Station for COPQ [70]

The most expensive cost is when the defect changes the customer's opinion for the product or service offered. In the end it affects the brand name and perceived value of work. Losing customers means losing business.

1.1.3 INJECTION MOLDING

Injection Molding is a process where molten plastic material is filled inside a mold and then a molded part is produced when the plastic solidifies. This process is preferred for mass production of complicated geometries and plays an important role in plastic industry. The process is comprised of mold clamping, charging, injection, cooling, mold opening and part ejection. The process is carried out using injection molding machines usually two and three platens. It consists of an injection unit, a mold and a clamping unit and needs electrical power along with utilities like compressed and chilled water [27]. The injection unit plasticizes plastic pallets into molten plastic and injects it inside the mold while the clamping unit performs the mol opening and closing function before and after injection [28]. Products of molding process are the plastic part and at times the sprues or runners. Sprues or runners are not part of product and are used after being re-grind with the virgin material in some ratio [29].

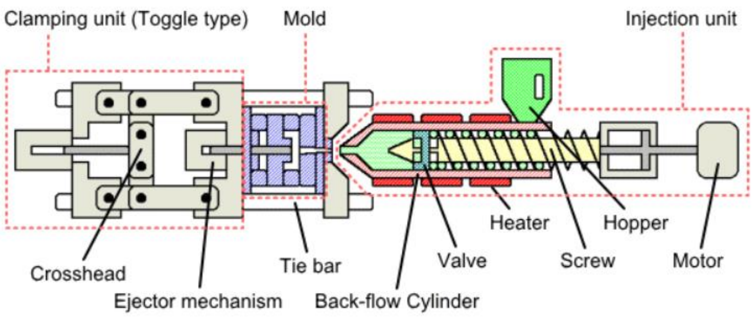

Figure 1.3 Injection Molding Machine top view [71]

Molding process is a combination of multiple inputs where the most important are the grade of plastic used, cylinder temperature, injection and plasticization speeds and pressures and cooling times [30]. Hence, experience and better technology matters for the most suitable set of parameters to operate molding machines.

1.1.4 TYPES OF INJECTION MOLDING DEFECTS

Although injection molding supports for high volume production of complex geometries and aesthetics, but with so many different input variables come more chances of errors and a minor mistake at the time of development can lead to major operational issues. Defects on plastic parts are a result of mistakes in parameters or issue in mold geometry. These show on parts as visible and at times as non-visible defects.

Flow Lines: These appear on surface of parts as off-color lines, patterns, and streaks. This happens due to uneven cooling of molten plastic because of sudden difference in injection speeds hence affecting the cooling rates [31]. Other reasons can be difference in wall thicknesses and sudden appearance of walls and edges where material flow drastically changes.

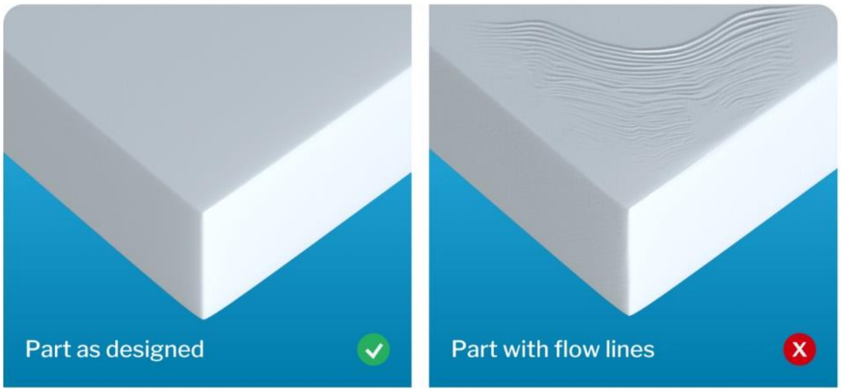

Figure 1.4 OK and NG part for Flow lines [72]

Sink Marks: These may appear as dents or craters on a part and are a result of contraction or shrinkage at different rates of those areas of part where the thickness is greater and the material inside takes time to cool [32].

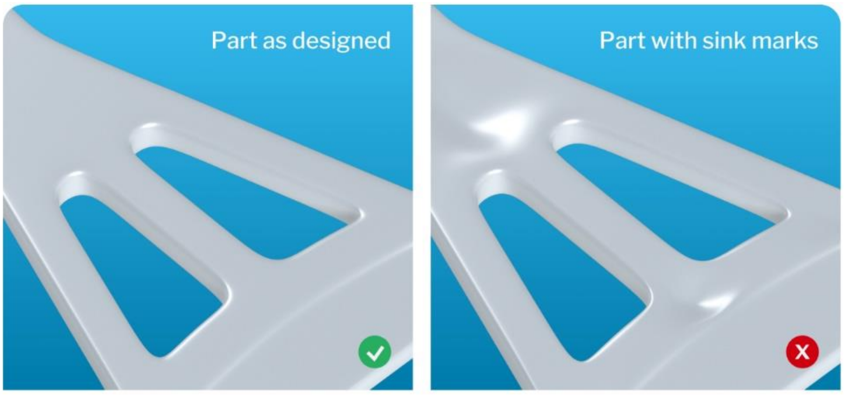

Figure 1.5 OK and NG part for sink marks [72]

Weld Lines: These occur when two flows join inside the cavity of the mold usually due to obstructions like pins and holes. Due to temperature difference between the two flows, the molten material doesn't bond together and form a visible weld line [33].

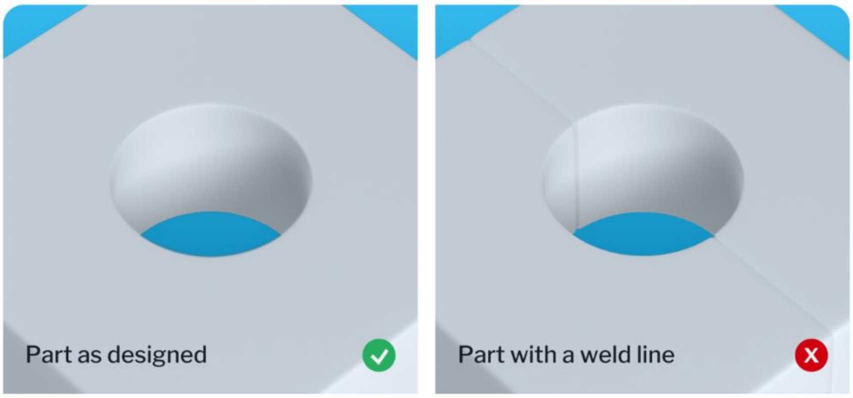

Figure 1.6 OK and NG part for Weld Lines [72]

Short Molding: Short shots are due to material not being filled inside the cavity of mold. It happens usually when material faces resistance during injection through the nozzle, due to trapped air inside mold cavity, insufficient injection pressures, low charging parameters, any foreign particles blocking the mold gates, high viscosity of molten material, low mold temperatures etc [34]. Hence it is advisable to have proper vents in molds and keeping mold surface temperature on the higher side.

Figure 1.7 OK and NG part for Short Shot [72]

Warping: It refers to the bending or the part getting de-shaped due to insufficient cooling time being given to the part which results in uneven cooling because of difference in part thickness [35]. This can also be said as the reaction of residual stresses inside the part.

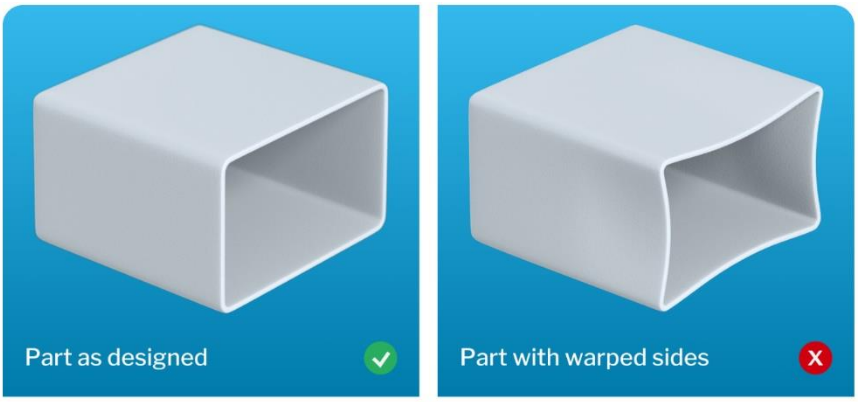

Figure 1.8 OK and NG part for Warpage [72]

1.1.5 TYPES OF INDUSTRIAL PAINTING TECHNIQUES

As the industry is expanding worldwide, several new painting techniques have been developed to achieve faster, more efficient, and cost-effective processes to compete in cost and quality. Compared to residential or commercial painting, industrial techniques make use of advanced machineries and methods to ensure that the product is durable and has resistance to the changing harsh environment [36]. Some of the most used techniques have been explained below.

1.1.5.1 DIP COATING METHOD

It is a much reliable technique for projects being carried out in industries where a bulk number of products are manufactured. It required object to be immersed in the liquid film substance after which it is drawn and left to dry. It is usually used where a thick layer of paint is required on the part. The critical parameter here is the time required to draw-off the object from the liquid as it decides the amount of paint coated on the surface [37].

1.1.5.2 SOLVENT-BASED COATING METHOD

Such paints contain organic adhesives and liquefying agents. This is used in industry as it has fast drying time, has resistance to extreme weather conditions and changes in temperatures. Further it hides surface imperfections by giving a protective layer and a durable finish [38].

1.1.5.3 AIR SPRAY METHOD

This is the most favored method for industrial and commercial use by painters where paint is applied using combination of pressurized air through a spray gun along with paint solution. This combination is also known as atomization [39]. The output texture, paint pattern and consistency vary with difference in nozzle diameter and air pressure levels.

1.1.5.4 ELECTROSTATIC AIR SPRAYING METHOD

This is modern paint application technique and extensively used in the automobile industry due to its high-quality output where the surface evenness is a critical quality parameter. This process ensures smooth coverage on surfaces like metals, doors, and fences. This needs specialized HVLP (High Volume Low Pressure) sprayers and air-assist guns. The HVLP sprayers use high voltage so that paint sticks to the surface ensuring a solid and smoother finish [40].

1.1.5.5 AIR LESS PAINT SPRAYING METHOD

This method is used on large scale for glossy and glass-smooth textures. A hose pumps paint through the nozzle attached to it and relies mainly on controlled flow rather than compression. The liquid film is held together by surface tension and viscosity collectively while the flow from nozzle dissipated the painting mist evenly. Hence the procedure ensures smooth coating by eliminating the chances of over-spraying [41].

1.1.6 TYPES OF PAINTING DEFECTS

Paint being a combination of multiple things like resins, fillers, solvents, and additives, is formulated for a wide range of applications and conditions. Therefore, it must be applied and cured correctly to ensure the desired results [42]. If not handled with care and all the pre-requisites, several defects can be observed from which some are discussed below.

Pinholes, also known as craters, are small holes on painted surface and are formed due to inclusion of air and due to residual strains in the part on which paint is applied [43].

Cracks appear on painted parts due to attack by a particular solvent in paint. It is often seen in acrylic painting and occur near edges and gate points. The areas prone to attack are those where residual strains are high and cause chemical stresses [44].
Sinking is another type of cracks but here paint penetrates inside the component and again the areas prone to attack are gate points, edges, and welds [45].

Crawling is 1mm+ indentation on component surface where the substrate becomes visible and occurs due to low paint adhesiveness on component surface [46].

Orange peel is the surface of component taking appearance of an orange with numerous small indentations and bumps [47].

Lifting, also known as wrinkling is the peeling off from the painted surface when it is applied on another layer of paint(repainting).

Here our concerned defect is **CRACKS** which is basically a mixture of hidden molding defect of flow marks where the paint mixture attacks and shows up as cracks.

1.2 OVERVIEW OF INDUSTRY

Pakistan's industry of home appliances has a wide range of products which include Washing Machines, Water Dispensers, Split ACs, Ovens etc. in major appliances while dishwashers, grills, roasters, vacuum cleaners etc. in small appliances. Retail sectors refer to home appliances as white goods. [48]

These products play an important role in people's life by aiding in daily household chores. Due to technological advancement in the recent years, this industry has been on a boom. As the living standards, need for comfort and disposable income of people is increasing, the need to upgrade the current version of these appliance is also increasing. Pakistan's home appliance industry contributes to about 10% in GDP with people spending about 2-3% of their income on home appliances. As inhouse production of raw material is currently not being practiced in Pakistan, the manufacturers of white goods have to import this raw material round the globe resulting in the cost of home appliances being on higher side. One of the major competitors for Pakistan is China which is the home for appliances industry. Although reducing the COPQ without affecting the quality for any product can be very challenging yet it helps in competing in local market as cost reduction is the ultimate game changer in manufacturing industry [49].

Here in this study, reduction of COPQ for Water Dispensers produced in the largest firm of home appliances will be discussed in detail. There are three major types of water dispensers produced at this firm which are as follows:

1. Plastic Door
2. Glass Door
3. Plastic Door (Without Ref)

Below is the product line of home appliances produced in the firm:

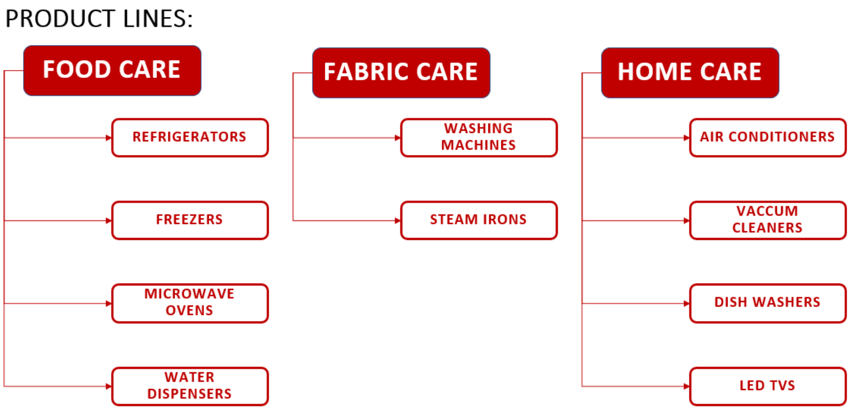

Figure 1.9 Product Line for Dawlance Pvt Ltd

.9

Figure 1.10 Glass Model [73]

Figure 1.11 Plastic Model (w/o Ref) [73]

Figure 1.12 Plastic Model [73]

It has 3 models and 10 variants currently in production:

S No	Item Codes (Derived)	Item Description
1	F01000000102	WATER DISPENSER WD-1051 GBR CHAMPAGNE
2	F01000000106	WATER DISPENSER WD- 1060 WBR SILVER
3	F01000000140	WATER DISPENSER WD-1051 SILVER
4	F01000000103	WATER DISPENSER WD- 1060 WGR CHAMPAGNE
5	F01000000281	WD-1060 FP WHITE
6	F01000000245	WD-1051 CLOUD WHITE
7	F01000023000	WD 1051 MAROON
8	F01000022800	WD-1051 RED

9	F01000022700	WD-1051 NOIR RED
10	F01000022900	WD-1051 BEIGE

Table 1.1 SKU wise list for WDs produced

1.3 MANUFACTURING FIRM PROFILE

This manufacturing firm produces the plastic parts for Water Dispenser inhouse in its injection molding facility which has 21 machines ranging from 125T to 2600T. The plastic parts produced are made from ABS material. Some models are painted for better texture while some models are produced with the masterbatch resin added in ABS material as per the product marketing team. Firm has its own painting facility where plastic parts are painted using air spray method. Pressurized air of 5.5 bars is used in air guns and paint mixture is applied on the parts.

There are four critical plastic parts of water dispenser.

1. Top Door Front – Glass Door Model (Fig 1.10)
2. Top Door Back – Glass Door Model (Fig 1.12)
3. Ref Door – Glass Door Model (Fig 1.13)
4. Ref Door Cover Front – Plastic Door Model (Fig 1.11)

Figure 1.13 Top Door Front

Figure 1.14 Ref Door Cover Front

Figure 1.15 Top Door Back

Figure 1.16 Ref Door

1.4 PROBLEM STATEMENT

The problem which was being faced was during painting process. The parts have injection points on the aesthetic surfaces as shown in the pictures above. After application of paint, flow marks appear near these injection points which are initially not visible on the unpainted part. As the issue was not visible on unpainted parts, primer was used on every part to provide a protective layer for paint to stick to surface. The results after paint are shown below in Fig 1.14:

Figure 1.17 Flow marks on painted parts

This was adding to the cost of poor quality (COPQ) as rework cost and t**his money was to be saved from being wasted as COPQ**

1.5 RESEARCH OBJECTIVES

Profitability of organization is always the target of any industrial project where reduction in COPQ is one of the factors to achieve this target. Therefore, objective of this study was to cut down the capital wasted against the COPQ.

To specify, following were the research objectives:

1. To **reduce** the defects of flow marks from plastic painted parts.
2. To **minimize** the cost of poor quality per product.
3. To create a model of **six sigma study** with **Design of Experiments** for problem solving and finding out the relation between input variables

1.5.1 RESEARCH QUESTIONS

The purpose of this research is to reduce the cost of poor quality incurred in painting the molded parts hence this study answers the following questions:

1. What Road map production engineer must follow for general problem solving where the solution is completely or partially unknown?

2. What variables affect the painted part quality?
3. What are the critical variables for part quality?
4. Where else this problem-solving model can be implemented?

1.6 SCOPE AND LIMITATIONS

For the scope of this study, water dispenser product category was considered during this entire study, and this was limited to injection molding process, paint application and use of ABS plastic resin for injection molded parts.

CHAPTER 2
LITERATURE REVIEW

Several research have been conducted on six sigma methodology, DMAIC, lean manufacturing tools and their usage, injection molding process and its defects, and painting process defects on plastic molded parts from which much known ones related to this research are discussed below.

2.1 LEAN SIX SIGMA:

- Esther Akinlabi, Fredrick Madaraka Mwema, Omolayo M. Ikumapayi and Okwudili Ogbonna (2020) gave an overview of six sigma and lean manufacturing that how in modern manufacturing, companies are targeting least cost, least non-value-added processes and increased outcomes all on the basis of lean six sigma manufacturing which ensures that without compromising product quality, keeping risks low and without material wastage, customer satisfaction is achieved. It helps companies focus on developing efficient material flows and minimizing inventory cost along with minimal wastages. As lean focuses on minimizing the wastages while six sigma focuses on reducing the variation in process, a combination of both can help companies boost profits exponentially [50].

- Pankajh M. Madhani (2020) in his research of lean six sigma methodology concluded that retailers must be having a proactive approach for competing in the progressing market if it wants to outperform its competitors in the market. Lean Six Sigma can provide retailers ability to create a difference and help to fulfill customer's needs and requirements. LSS provides the specific tools for the retailers to define, measure, analyze and improve the inefficiencies and the poor outcomes. It will help the retailed to streamline the processes and reduce the risk of variations from the outcome [51].

- P. Rewers and J. Trojanowska (2016) discussed the tools related to Lean Manufacturing concluding that if these tools are used by a company, it will help to eliminate waste faced during production and achieving the goal of improved production. These tools include Kanban, Heijunka, VSM, Poka-Yoke, Jidoka, Kamishibai, 5S, TPM, SMED and Kaizen. The literature available on this topic is waste and only limited and most common tools are discussed [52].

- B. Radha Krishnan and K. Arun Prasath (2013) mentioned about the basic toold used in six sigma when DMAIC methodology is being followed. Starting from its history in Motorola, and then discussing what six and sigma actually mean, they explained the entire methodology starting from Define, Measure, Analyze, Improve and Control and the specific tools which are used in each phase [53].

2.2 COST OF POOR QUALITY

- S. N. Teli, V. S. Majali, U. M. Bhushi and L. M. Gaikwad (2013) carried out a case study in an Indian automobile firm to find out the cost of good and poor quality to come to a conclusion that as the product come closer to the customer, its cost of quality increases hence it is essential to manage the quality system in such a way the even if prevention cost is bear by the company, it will save it from many severe pitfalls, decrease in quality of product or service, increase in customer dissatisfaction and added costs of rework. Achieving higher level of quality by using improved process controls will end up reducing the overall quality cost as well as the marker share, customer satisfaction etc [54].

- S. N. Teli, V. S. Majali, U. M. Bhushi and V. G. Surangi (2012) discussed a case of Toyota Motors where a minor defect resulted in a major loss of brand name and loss in the terms of service cost. Hence a set of optimized quality controls can give exponential results when talking about revenues and brand name. To create a product of high consumer satisfaction, it is much needed to reduce the production costs and improve processing speeds while ensuring that quality is not compromised. Investing on quality controls can help reduce the wastages, help improve the quality outputs, reduce variations, and ultimately protect the brand name and customer satisfaction [55].

2.3 INJECTION MOLDING PROCESS AND DEFECTS:

- C. Fernandes, A. J. Pontes, J. C. Viana and A. Gasper-Cunha (2018) carried out research to observe the different phases of injection molding process like filling, post filling and plasticizing and see the optimization of these parameters through mathematical modelling. It also focuses on the optimization of features associated with runner systems, process conditions, gate locations and cooling channels. All the phases were described in detail through mathematical formulas [56].
- Louis Tredoux and Isao Satoh (2000) conducted research to investigate wave like flow marks on plastic molded parts which is one of the most common surface defects in injection molding process. It is mostly observed in areas where injection speeds are low, for e.g., walls or any obstructions. According to the results of experiments, increase in velocity of molten material as well as the increase in mold temperatures can help reduce these flow marks. Also, the type of material plays a key role in appearance of the flow marks hence it is necessary to design molds w.r.t the material being used as materials have different behaviors in different molds [57].

2.4 PAINT DEFECTS:

- David Palmer (2014) conducted research to identify the effects of paint on different types of plastic ABS by doing multiple experiments using black and clear adhesion promoter and topcoat. He concluded specifically for general purpose ABS which is mostly used in the plastic industries that the impact strength is maximum when there is no topcoat and adhesion promoter while reduces by almost **25%** if topcoat is applied with black adhesion promoter. Similar were the results **for tensile modulus, tensile strength, strain at yield and strain at break**. He concluded that it would be a mistake to specify a painted plastic with a given application without considering the effect of the paint system on the mechanical properties of that plastic. The effects of paint are not always detrimental but need to be checked for successful application and results as it is the combined effect of chemical and mechanical factors which at times can be difficult to predict [58].

- Eponine Renaud, Evelyne Darque-Ceretti, Bernard Monasse, Philippe Duquesne and Frederic Georgi (2017) conducted research regarding the visual defects of painted surfaces on ABS/PC injected parts. ABS-PC was injected in two different molds with no visible surface defect. After painting process was applied as per the industrial procedure, the defects near injection gates of mold as well as near the weld line were visible. It was interpreted after microscopic study, that due to some solvent in the paint, the invisible molding process defects are further enhanced and become visible after application of paint. These defects are part and parcel of painting solvents and can be reduced or eliminated by number of methods like **modification of processing conditions** to prevent crack initiation and propagation, **modification of mold geometries** to avoid complex material flows (parting line and weld line**), curing between the application** of topcoat and base-coat to allow the gases to evaporate and not let the cracks propagate, **changing in the solvent composition** of paint to reduce the adverse effects on plastic parts [59].
- David Palmer (2014) conducted another study on the effects of paint on different types of plastics for e.g., Weather Resistant-ASA, High Impact ABS, General Purpose ABS and PE Ionomer. There are several ways paint can affect plastic. Paint solvents etches the plastic surface. At times this etching is necessary to achieve the maximum adhesion of paint to the plastic surface. Paint solution can cause **surface crazing** as well as the **surface degradation of plastic** like swelling softening and dissolution of polymer. Certain amount of this is helpful but if it goes to extreme levels, it degrades the plastic quality as well its mechanical properties. Therefore, this diverse effect isn’t usually used for adhesion instead primers are applied of plastics to ensure perfect surface adhesion of paint. The plastic polymer samples were tested with different combinations, and it was found that the results were so diverse that it was **difficult to interpret and predict** a perfect combination for any plastic part. It also depends on the **plastic material type** as it plays an important role on the behavior against paints [60].

The papers discussed above give us an understanding related to the importance of implementing six sigma and lean manufacturing on industrial level to achieve increased profits and reduced wastages. The papers focus on injection molding process and its defects which play a role in post painting defects. These molding problems are mostly related to material specification as well as the operating parameters of the molding process which are usually not visible by naked eye and get visible after application of paint.

CHAPTER 3
RESEARCH METHODOLOGY AND DATA COLLECTION

Six sigma methodology focuses on solving the problems where answers are completely unknown and provides us a direction with its important tools to work on the critical factors. This paper uses DMAIC approach to reduce the defect of flow marks seen after painting process on plastic molded parts. This is done in 5 different steps starting from problem identification, followed by measuring of the faults, analyses of the measured data, improvement, and control. The detailed implementation of DMAIC is carried out in below sequence.

3.1 DEFINE

The first phase of DMAIC is problem definition. The work was initiated with identification of the problem phased in painting process of plastic molded parts of water dispenser. It was needed to reduce the rework being done with primer so that the overall transformation cost is reduced.

3.1.1 CURRENT SCENARIO

Currently, WD is having a high COPQ due to the rework being done to hide the flow marks which appear after application of paint by applying a coating of primer as these flow marks are not visible on the unpainted molded parts.

Fig 3.1 shows breakup of the cost being incurred per product during last 4 years

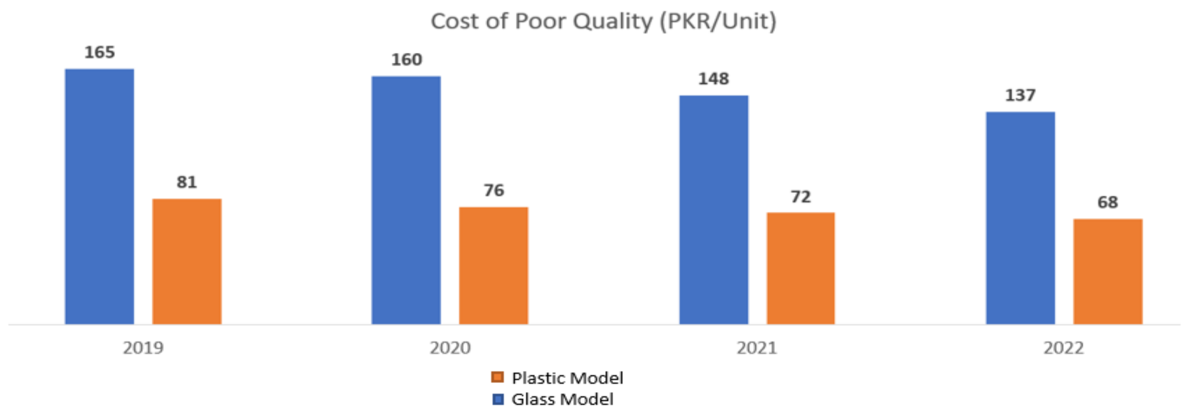

Figure 3.1 Cost of Poor-Quality comparison for plastic and glass models of WD

For finding the current scenario, 400 parts were painted each day which included application of primer and number of defective parts were counted for the next 31 days. These parts were not rejected after the experiment as they were used for routine production of water dispensers in the firm. The data was plotted on Minitab (software for statistical data analysis) and Fig 3.2 shows the results:

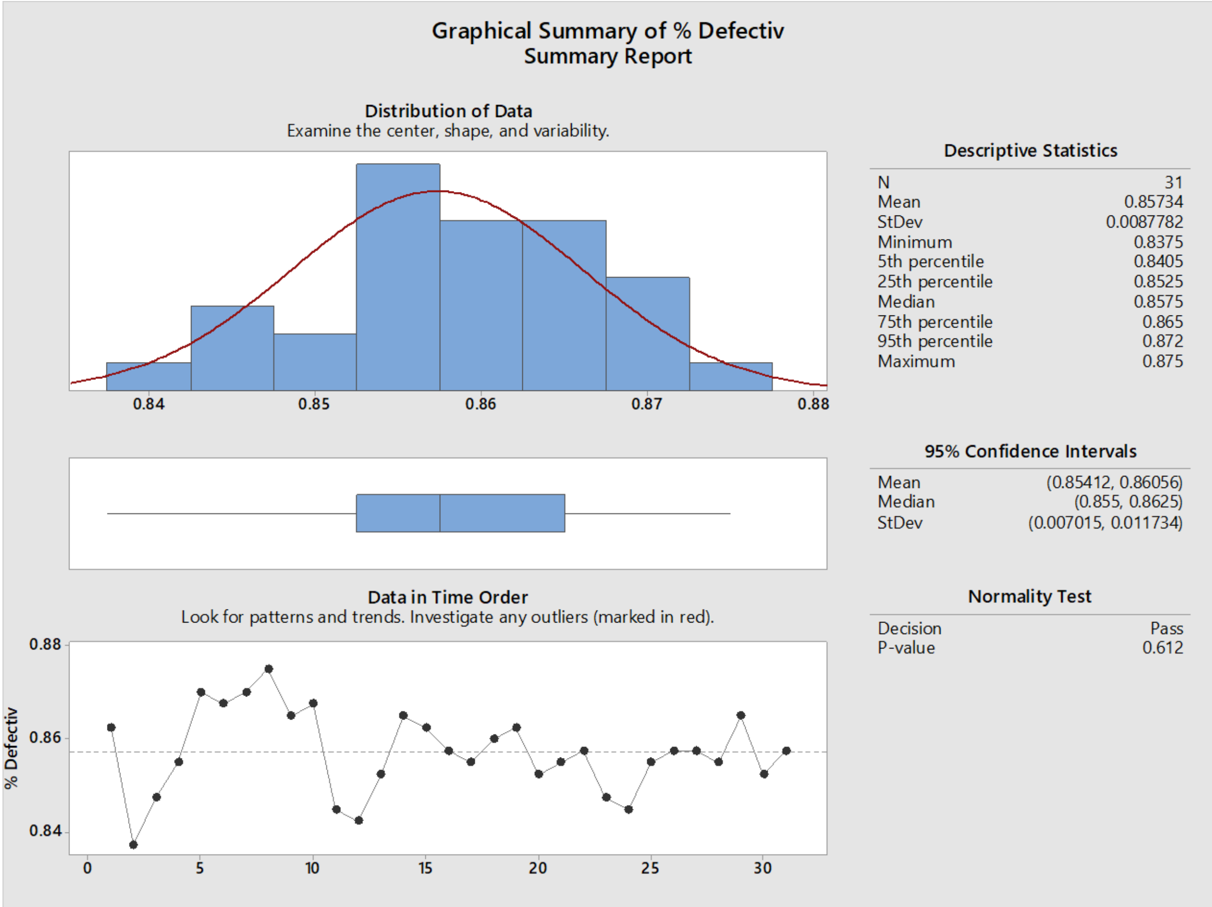

Figure 3.2 Graphical Summary of current observations

The sample has at least 30 observations and it passes the normality test where p value is greater than 0.05. For any data to be normal, it is necessary, that its p-value is greater than 0.05. P value is the probability that the null hypothesis is rejected while in fact it was true.

The mean of the data was 85.734% which meant that 85%+ parts were found defective and had to be reworked with primer. Data had very negligible variation of 0.877% with no anomalies. The time order graph showed that the variation was random and had no special causes.

The 25^{th} quartile value was 85.25% while the 75% quartile value was 86.5% which shows that the 50% of the data within had a variance of 1.25% and the central value being 85.75% was more towards the 25^{th} percentile.

3.2 MEASURE

The measure phase enables us to understand the problem and the factors which cause it to happen through multiple tools like FMEA, Priority Matrix, Fishbone Analysis etc [61].

3.2.1 UNDERSTANDING THE PROCESS FLOW

Injection Molding, although simple processes but require highly skilled and technical team to carry them out [62].

These processes can be seen in the process flow diagram in Fig 3.3 below:

Figure 3.3 Process Flow for Injection Molding process

Above is the injection molding process flow starting with the mold closing and ending on part retrieval. The critical inputs to the injection molding process are the injection, charging, packing, suck back and cooling because these functions alter the final part quality [63]. High technical skills are needed to carry out injection molding process via the injection molding machines.

The process starts with the step of mold closing. After the punch and cavity of the molds are close, the machine applies a high pressure and so that they completely are clamped. The core functions take place and the material which was charged in the last cycle is injected in the cavity of mold. The screw in the injection barrel puts a final push on the material so that it gets filled in all the smallest cavities in the mold. The main functions within are core movement, charging, injection and cooling [64].

Although the process seems very simple yet there are multiple inputs for each step shown like pressure, speed, position, time and force.

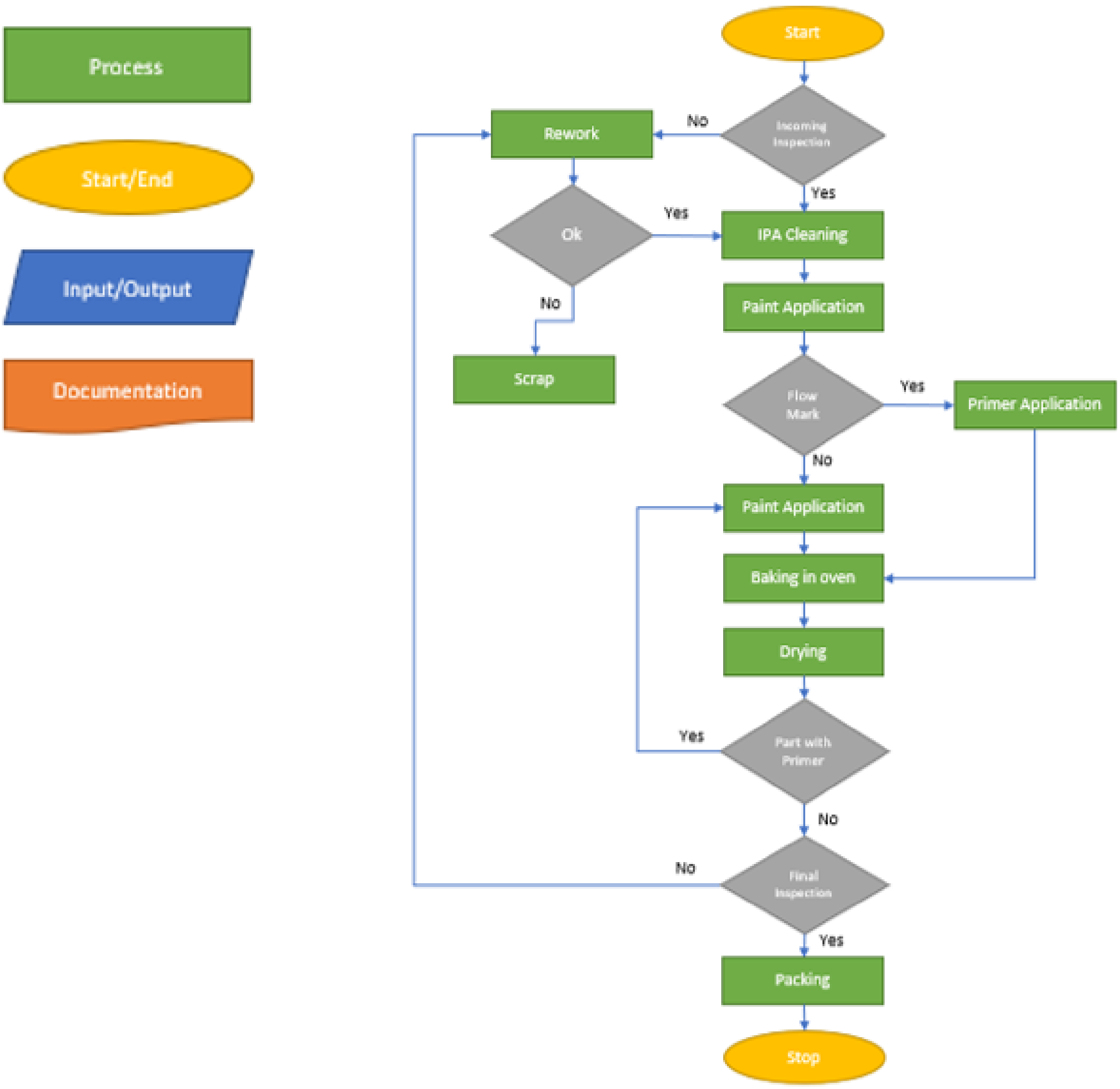

Figure 3.4 Process Flow for Paint process

Fig 3.4 above is the spray-painting process which starts with the incoming quality inspection of part. If the part is OK, it is cleaned with special duster cloth using IPA degreasing agent. Paint is applied using spray gun with 5.5 bars air pressure. The paint recipe is defined for each part according to the gloss and thickness level as specified by the engineering and quality team. After application of paint, the parts are cured in baking oven for 20 minutes at 50-60 degrees temperature. Part is then dried in air.

If there are any flow marks visible on the part after paint application, primer is applied on the surface and painted again. In case if every part shows up these flow marks, primer is applied before paint application, followed by painting, baking and drying.

3.2.2 ROOT CAUSE FOR FLOW MARKS ON PLASTIC PARTS

A root cause analysis was much needed here to bring in limelight all the possible factors which could contribute to appearance of these flow marks. It consists of three tools:

1. Fish Bone Analysis
2. Priority Matrix
3. Failure Mode and Effect Analysis (FMEA)

3.2.2.1 FISH BONE ANALYSIS

A more structured approach was needed to find out the possible root causes of this flow marks issue on painted parts hence a detailed root cause analysis was done for this effect. The causes were distributed in 4 categories named Man, Method, Material and Machine

Further the root causes were marked with being Noise, Procedural or Controllable.

Noise root causes are those which cannot be predicted or controlled like thunderstorm, rain, traffic jam etc. Procedural root causes are those which depend on methods or Work Instructions and can be avoided by introducing new work instructions or improving the already practiced methods. Controllable root causes are those which can be avoided by putting effective prevention control tools like Poka-Yoke etc. [65].

Fig 3.5 shows the root cause analysis for flow marks on painted plastic parts.

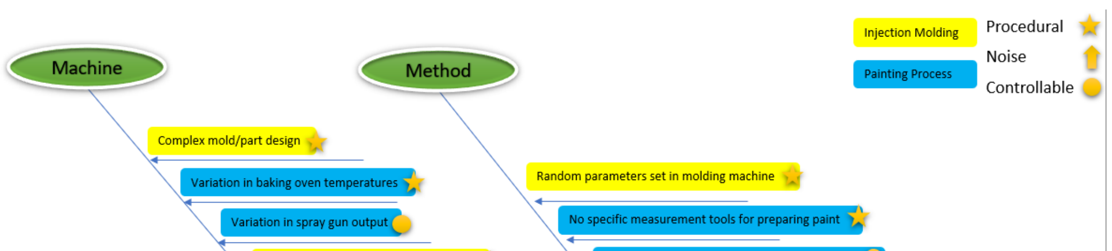

Figure 3.5 Fishbone Analysis of Flow marks on painted parts

3.2.2.2 PRIORITY MATRIX

After the root cause analysis was completed using fish bone/Ishikawa diagram, it was needed to filter the root causes according to the priority. Priority matrix is normally prepared using the experience of technical staff for the processes under consideration. The priority matrix finalized for the fishbone is shown below in Table 3.1:

S. No	Shop	Importance rating		1	2	Total rank
		Outputs		Flow marks on **unpainted part**	Flow marks on **painted part**	
		Inputs/Weights	Weights	10	9	
1	IM	Complex mold/part geometry		3	9	111
2	PS	Variation in spray gun output		1	3	37
3	PS	variation in baking oven temperature		1	9	91
4	IM	variation in machine packing pressure		3	3	57
5	IM	variation in machine injection pressure		3	3	57
6	PS	Manual paint by painter		1	3	37
7	PS	Manual paint preparation		1	3	37
8	PS	Man-dependant paint preparation		1	3	37
9	IM	Random parameters set in molding machine		1	3	37
10	PS	No specific tools for preparation of paint		1	3	37
11	PS	no specified painting method		1	3	37
12	PS	usage of thinner in paint		1	9	91
13	PS	Usage of wrong paint/hardener/thinner hardness		1	9	91
14	IM	Material of plastic part not as par the actual requirement for paint		1	9	91

Table 3.1 Priority Matrix

This priority matrix shows that the yellow highlighted five points are mainly responsible for these flow marks appearing on plastic parts before and after paint hence these are the points needed to be worked upon. The table shows that around 52% of the risks are due to these 5 points out of the 14 points highlighted from the Ishikawa diagram.

1. Complex mold/part geometry
2. Variation in baking oven temperature
3. Usage of thinner in paint
4. Usage of wrong paint/hardener/thinner ratios
5. Material of plastic part not as per the actual requirement for paint

Further it will be analyzed that which of these 5 points can be improved and where do we have process/cost limitations.

3.2.2.3 FAILURE MODE AND EFFECT ANALYSIS (FMEA)

Failure Mode and Effect Analysis, also names as FMEA, is a systematic approach to identify where can a process fail and what can be the reasons for its failure. Every potential root cause is given an RPN number which is the risk priority number. It is the product of severity, occurrence, and detection. All these three factors have a table according to which the number is given to the root cause [66]. Table 3.2 below is used to give **occurrence score**:

Chances of Failure	**Criteria: Occurrence of cause – PFMEA (Incidents per items/product)**	**Rank**
Very High	100/1000, 1/10	10
High	50/1000, 1/20	9
	20/1000, 1/50	8
	10/1000, 1/100	7
Moderate	2/1000, 1/500	6
	0.5/1000, 1/2000	5
	0.1/1000, 1/10,000	4
Low	0.01/1000, 1/1,000,00	3
	≤ 0.01/1000, 1/1,000,000	2
Very low	Failure be eliminated by preventive controls	1

Table 3.2 Occurrence score table for FMEA [67]

Table 3.3 below is used to give **severity score**:

Effect	CRITERIA: Severity of effect on the product	Rank	Effect	CRITERIA: Severity of effect on process
Failure to meet safety and / or regulatory requirements	Potential failure mode affects safe Product operation and/or involves noncompliance with government regulation without warning.	10	Fail to meet safety or regulatory requirements.	Can endanger operator, machine or assembly without any visible warning.
	Potential failure mode affects safe product operation and/or involves noncompliance with government regulation with warning.	9		Or may endanger operator, machine or assembly with some warning.
Loss or degradation of any one of the primary functions	Loss of primary function (Product may not operate but does not affect safe Product operation)	8	Some Major Disruptions	100% of the product may be scrapped. Line may shutdown or stop shipment.
	Degradation of primary function (Product operable but at a compromised level of performance)	7	Significant Disruption	A portion of the production might be scrapped. Deviation from the primary process may occur including reduced line speed or addition of manpower.
Loss or degradation of any one of the secondary functions	Loss of secondary function (Comfort/Convenience functions inoperable)	6	Moderate Disruption	100% of the product may have to be reworked offline and accepted.
	Degradation of secondary function (Comfort/Convenience functions operable at a reduced level of performance)	5		A portion of the production might be reworked offline and conditionally accepted.
Annoyance	Appearance or audible noise, Items do not conform and can be noticed by most customers (>75%)	4	Moderate Disruption	100% of the production run might be reworked in station before it is further processed.
	Appearance or Audible noise, Items do not conform and can be noticed by many customers (50%)	3		A portion of the production run may have to be reworked in station before it is further processed.
	Appearance or Audible noise, Items do not conform and can be noticed by discriminating customers (<25%)	2	Minor Disruption	Slight inconvenience to process, operation, or operator
No effect	No discernible effect.	1	No effect.	No discernible effect.

Table 3.3 Severity score table for FMEA [67]

Table 3.4 below is used to give **detection score**:

Opportunity for Detection	Criteria: Likelihood of detection by process control	Rank	Likelihood of detection
No detection opportunity at all	No current Process Control; Cannot detect or is not analyzed.	10	Almost Impossible
Problem detection after processing	Failure Mode is not easily detected (E.g.: Random Results)	9	Very Remote
Loss or degradation of any one primary function.	Failure Mode detection before processing is done by operator through visual detection or audible means.	8	Remote.
Problem Detection at source	Failure Mode detection by operator through visual or audible means or post processing through use of attribute checks (go / no-go, manual torque check / clicker wrench, and things like these).	7	Very Low
Problem Detection after processing	Failure Mode detection post-processing by operator through use of variable gauging or in station by operator through use of attribute gauging (go / no-go, manual torque check / clicker wrench, etc.).	6	Low
Problem Detection majorly at source	Failure Mode or cause detection at the station by operator by use of variable gauging or by automatic controls on the station. Gauging performed on set up and first piece check (for setup causes only)	5	Moderate.
Problem Detection after the processing	Failure Mode detection post-processing by automated controls that will detect discrepant part/product and lock part/product to prevent further processing.	4	Averagely high
Problem Detection at the source	Failure Mode detection in-station by automated controls that will detect difference in part/product and automatically lock part/product in station to prevent further processing.	3	High
Error detection and problem prevention.	Error detection in-station by automatic controls that will detect error and prevent discrepant parts/product from being produced.	2	Very High
Detection not applicable; Only error prevention	Error prevention because of fixture design, machine design or part/product design. Discrepant parts/ products cannot be made because item has almost been error proofed by process / product design.	1	Very Certain

Table 3.4 Detection score table for FMEA [67]

Final FMEA is shown below in Table 3.5:

PROCESS FUNCTION	POTENTIAL FAILURE MODE	POTENTIAL EFECTS OF FAILURE	SEV	POTENTIAL CAUSE OF FAILURE	CURRENT PROCESS				RPN	RECOMMENDED ACTIONS
					PREVENTION CONTROLS	OCC	DETECTION CONTROLS	DETEC		
INJECTION MOLDING PROCESS	FLOW MARKS AFTER PAINT	ASTHETIC ISSUES AFTER APPLICATION OF PAINT / HIGH COPQ	7	PART NOT SET AS PER PARAMETER SHEET	PARAMETER SHEET	1	PARAMETER SHEET	3	21	NONE
				MATERIAL OF PART NOT AS PER REQUIREMENT OF PAINT	NONE	8	NONE	8	448	TRIALS IN ALTERNATE MATERIAL WITH BETTER FLOW
				INTRICATE PART GEOMETRY - TOO MANY RIBS/WALLS	NONE	3	NONE	3	63	MODIFICATION IN MOLD AFTER TRIALS
PAINTING PROCESS	FLOW MARKS AFTER PAINT	ASTHETIC ISSUES AFTER APPLICATION OF PAINT / HIGH COPQ	4	PAINT MIXTURE NOT AS PER RECIPE	MEASURING BEAKERS	7	NONE	5	140	PAINT MIXER MACHINE
				USE OF THINNER IN PAINT MIXTURE	NONE	10	NONE	10	400	ALTERNATE FOR THINNER (DISTILLED WATER)
				BAKING TEMPERATURE OF OVEN NOT AS PER REQUIREMENT	BAKING OVEN PANEL	6	ALARMS IN BAKING OVEN	8	192	TO BE CHECKED AT DIFFERENT TEMPERATURES
				USE OF IPA FOR CLEANING (CONTAINS THINNER)	NONE	10	NONE	10	400	ALTERNATE FOR IPA

Table 3.5 Failure Mode & Effects Analysis table

The FMEA of both processes clearly show us that there are multiple factors which can be the cause of these flow marks on plastic parts after paint. Most of the points are having RPN number more than 400 which need to be adressed in this research later

1. Material of part not as per requirement of paint
2. Use of thinner in paint mixture
3. Baking temperature of oven not as per requirement
4. Use of IPA for cleaning

3.2.3 DATA COLLECTION PLAN

For the resolution of this problem, it was much needed to collect some data which will be analyzed further to come to the results and conclusions

3.2.3.1 DESIGN OF EXPERIMENTS

Considering the standard table for understanding and example:

LEVELS	INPUT FACTOR 1	INPUT FACTOR 2	INPUT FACTOR 3	INPUT FACTOR 4
LEVEL 1	X11	X12	X13	X14
LEVEL 2	X21	X22	X23	X24

Table 3.6 Standard Table for factors and levels in DOE

So according to the formula for runs, we would be having (2^4 = 16 combinations) as follows:

Runs	Factor 1	Factor 2	Factor 3	Factor 4	Output
1	X11	X12	X13	X14	Y1
2	X11	X12	X13	X24	Y2
3	X11	X12	X23	X14	Y3
4	X11	X12	X23	X24	Y4
5	X11	X22	X13	X14	Y5
6	X11	X22	X13	X24	Y6
7	X11	X22	X23	X14	Y7
8	X11	X22	X23	X24	Y8
9	X21	X12	X13	X14	Y9
10	X21	X12	X13	X24	Y10
11	X21	X12	X23	X14	Y11
12	X21	X12	X23	X24	Y12
13	X21	X22	X13	X14	Y13
14	X21	X22	X13	X24	Y14
15	X21	X22	X23	X14	Y15
16	X21	X22	X23	X24	Y16

Table 3.7 Standard table for combinations in DOE

3.2.3.2 FACTORS AND LEVELS FOR RESEARCH

For this research, according to the FMEA and priority matrix, the following factors were finalized:

1. Type of Material
2. Use of thinner in paint
3. Baking temperature
4. Use of IPA for cleaning

The magnitudes of these factors were two for our experiments; High and Low.

3.2.3.3 INPUT VARIABLES

The factors were determined and now the values were to be fixed for two levels. Each level will be discussed in detail:

1. **Type of Material**

Currently GP-22 is being used which is a type of ABS material. The main properties which affect the flow of material in the mold are density and melt flow index. The alternate material which was needed for the other level must be having lower melt flow index so that the craters which form near the gate points can be filled. ABS white SD-0150 has equal density while MFI 5 times lesser than GP-22 hence this was used among the available material options. GP-22 has MFI of 19g/10min while ABS White has MFI of 3.8g/10min.

2. **Use of thinner in paint**

Only two options were available either a yes or a no hence this factor was not continuous rather discrete and as an alternate water was used to see the effect of not using thinner in the paint mixture.

3. **Baking Temperature**

The baking temperatures defined by the baking oven supplier were a range of 50 to 60 degrees Celsius hence these became our high and low levels for temperature. As per the supplier, operating below 50 won't bake the paint on the part completely while operating over 60 can damage the belt conveyer which is installed in the baking oven

4. **Use of IPA for cleaning**

IPA (Isopropyl Alcohol) is a degreasing agent used during the pre-preparation of plastic parts or metals before paint. It is a hydrocarbon by its chemistry and helps in removing any dirt, wax, oil etc. from surface. Here for the experiments, it can be either used or not used.

Hence the input variable shows something as follows:

Level	Material	Use of thinner	Baking temperature (degree Celsius)	Use of IPA for cleaning
Level 1	ABS White (SD-0150)	Yes	60	No
Level 2	ABS GP-22	No	50	Yes

Table 3.8 Table for levels and factors for painting trials

3.2.3.4 TAGUCHI'S ORTHOGONAL ARRAY

The final table of input variables is finalized as shown above and using it, an orthogonal array is designed with number of experiments being 16 as calculated by the formula written in section 3.2.3.2.

16 experimental runs were finalized, and 50 repetitions for every experiment were carried out for each combination of input variables. Results were plotted in terms of defect percentages where defect was examined by the quality inspector who declared number of OK and NG parts from the trials and calculated the defect % accordingly.

The final table of experiments carried out is as follows:

Run	Material Type	Baking temperature (°C)	Use of thinner	Use of IPA	Defect %
1	ABS White	60	Yes	No	2%
2	ABS White	60	Yes	Yes	10%
3	ABS White	50	Yes	No	35%
4	ABS White	50	Yes	Yes	45%
5	ABS White	60	No	No	65%
6	ABS White	60	No	Yes	85%
7	ABS White	50	No	No	75%
8	ABS White	50	No	Yes	70%
9	GP-22	60	Yes	No	80%
10	GP-22	60	Yes	Yes	85%
11	GP-22	50	Yes	No	80%
12	GP-22	50	Yes	Yes	90%
13	GP-22	60	No	No	60%
14	GP-22	60	No	Yes	65%
15	GP-22	50	No	No	60%
16	GP-22	50	No	Yes	65%

Table 3.9 Final table of results for all runs

CHAPTER 4
RESULTS AND DISCUSSION

This section focuses on the results and the variations among the values, helping us to find the relation between inputs and outputs as well as the significant and non-significant factors.

4.1 ANALYSE

After getting the results in the form of table, it was needed to plot it in graphical form for further analysis of experiment and to check the relation between the input variables combined and separately on the results of each combination. The data was plotted in Minitab software for further analysis and the graphs generated will be discussed in detail.

4.1.1 F/P VALUES IN ANOVA

After ANOVA, following priorities were observed where for being significant, F -value must be greater than 4 while P value must be less than 0.1

FACTOR TYPE	F VALUE	P VALUE	STATUS
Material	4.32	0.062	Significant
Use of thinner	1.54	0.241	Non-Significant
Baking temperature	0.51	0.49	Non-Significant
Use of IPA for cleaning	3.87	0.095	Significant

Table 4.1 Table for F/P values from ANOVA

4.1.2 MAIN EFFECTS PLOT FOR DEFECT %

First graph generated was the Main effects plot for defect % using the mean of the results obtained.

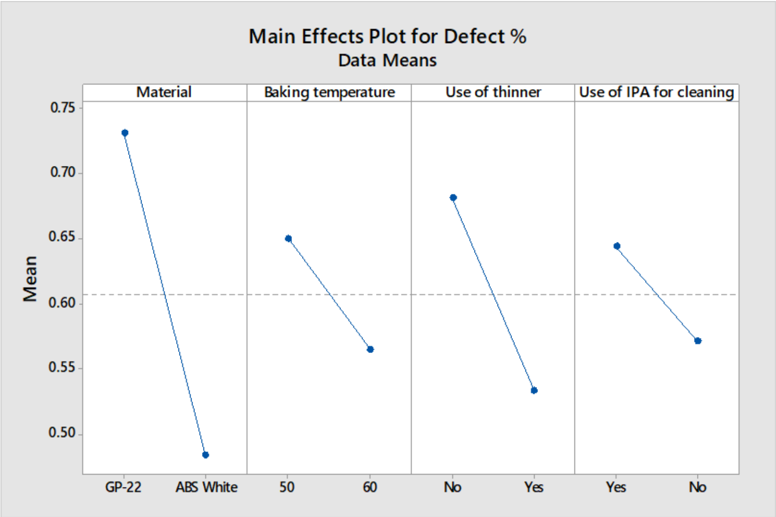

Figure 4.1 Main Effects Plot for Defect %

As it can be seen from the graph above, it shows the effect of 4 input variables independently on the results obtained. When material was the only variable and the other factors were not considered, the mean defect was 0.73 when using GP-22 and reduced drastically to 0.48 when ABS White was used to produce plastic parts.

When the temperature of baking oven was the only variable, the defect was 0.65 when the temperature was set to 50 degrees while 0.56 when set to 60 degrees. There was no major difference in changing the baking oven temperature on the part quality

When thinner was the only variable input factor, the defect rate was on lower side when thinner was used and on higher side when water was used in place of thinner to prepare paint solvent.

Use of IPA had a very minor difference on the defect rate when it was taken as the only input variable. With the use of IPA, the defect rate was on a higher side while without using IPA, it was on a lower side.

4.1.3 MULTI VARI CHART FOR DEFECT %

A multi-vari chart was also generated on Minitab to analyze the effect of all input variables interdependently on the results. The graph contains 4 panels

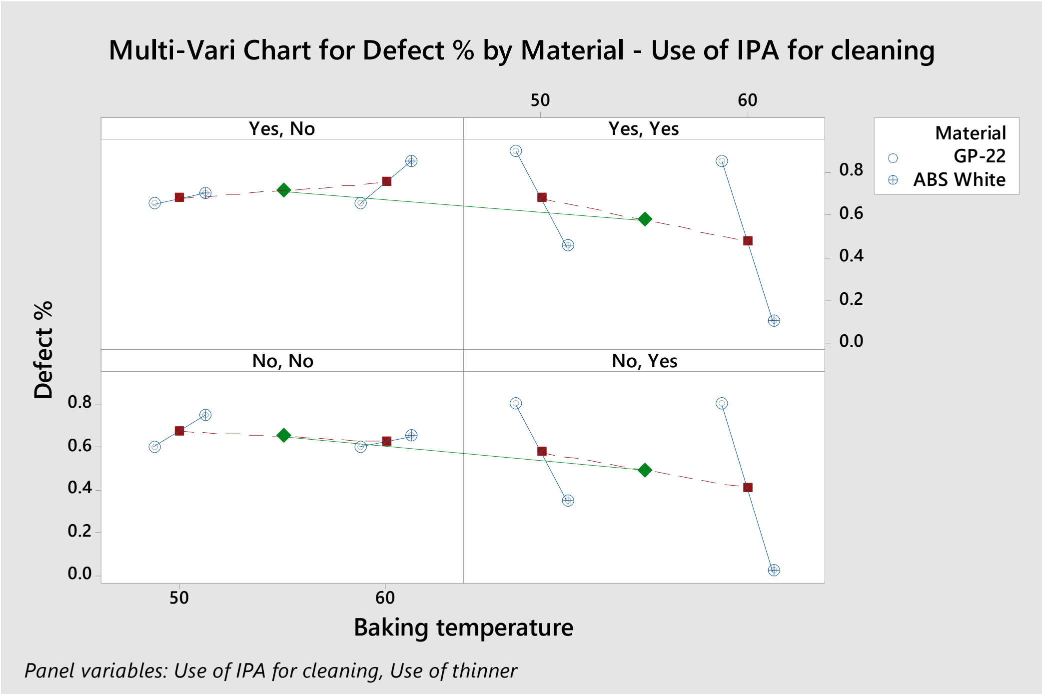

Figure 4.2 Multi-vari chart for Defect %

For understanding this graph, the panel variables are use of IPA and thinner. (Yes, No) in the panel means IPA is used and thinner is not used. The white circle represents GP-22 while the crossed dot represents ABS White. The Y- axis shows the defect rate from 0.0 to 1.0. The X-axis shows the temperature of baking oven from 50 degrees to 60 degrees Celsius. The red markers are the average defect ratio of both materials used to produce the plastic molded parts at 50 or 60 degrees Celsius, while the green dots are the average of the entire panel.

The least value of green marker is in panel 4 where IPA is not used for cleaning and thinner is used in preparing paint solvent. If we compare the effect of temperature, defect rate is lesser at 60 degrees Celsius while if we go next to the material type, using ABS White the defect rate further decreases drastically. Hence, we get to know the effect on defect rate with input variables being varied in different combinations.

Material here plays an important role in changing the output of our experiments when thinner is used with 60 degrees of temperature. This effect stays almost same when IPA is used for cleaning before paint or not used. When thinner is not used for making paint solvent, there is a very little change in defect rate and doesn't change much even though the use of IPA is changed with the change in oven's baking temperature.

This graph concludes that use of thinner and plastic material type has a drastic effect on part quality while use of IPA and baking temperature of oven has very minimal effects.

4.2 IMPROVE

After completing the analyze phase, it was needed to use our analysis on DOE for making a new combination of input factors to achieve the best results and to perform trials on that combination for validating it.

4.2.1 FINALIZED RESULTS

Below is the final table of our finalized results:

Material Type	Baking temperature (°C)	Use of thinner	Use of IPA for cleaning
ABS White	60	Yes	No

Table 4.2 Table of final combination of factors

The defect rate was the least with this set of input variables.

4.2.2 IMPROVED CHARTS

On the finalized input variables, sample parts were painted in 31 batches and each batch had 400 parts. Below are the results:

Batch Number	Parts Painted	Parts Reworked	% Defectives
1	400	10	3%
2	400	9	2%
3	400	8	2%
4	400	12	3%
5	400	10	3%
6	400	9	2%
7	400	8	2%
8	400	7	2%
9	400	8	2%
10	400	9	2%
11	400	10	3%
12	400	11	3%
13	400	10	3%
14	400	7	2%
15	400	8	2%
16	400	7	2%
17	400	8	2%
18	400	9	2%
19	400	8	2%

20	400	8	2%
21	400	7	2%
22	400	8	2%
23	400	9	2%
24	400	7	2%
25	400	10	3%
26	400	11	3%
27	400	7	2%
28	400	10	3%
29	400	8	2%
30	400	8	2%
31	400	9	2%

Table 4.3 Table for improved runs with results

The table clearly shows that on average, the defect rate was drastically dropped within 2-3% range validating or DOE study.

Again, this data was plotted on Minitab and some graphs were generated to study and analyze the results before and after the improvements done.

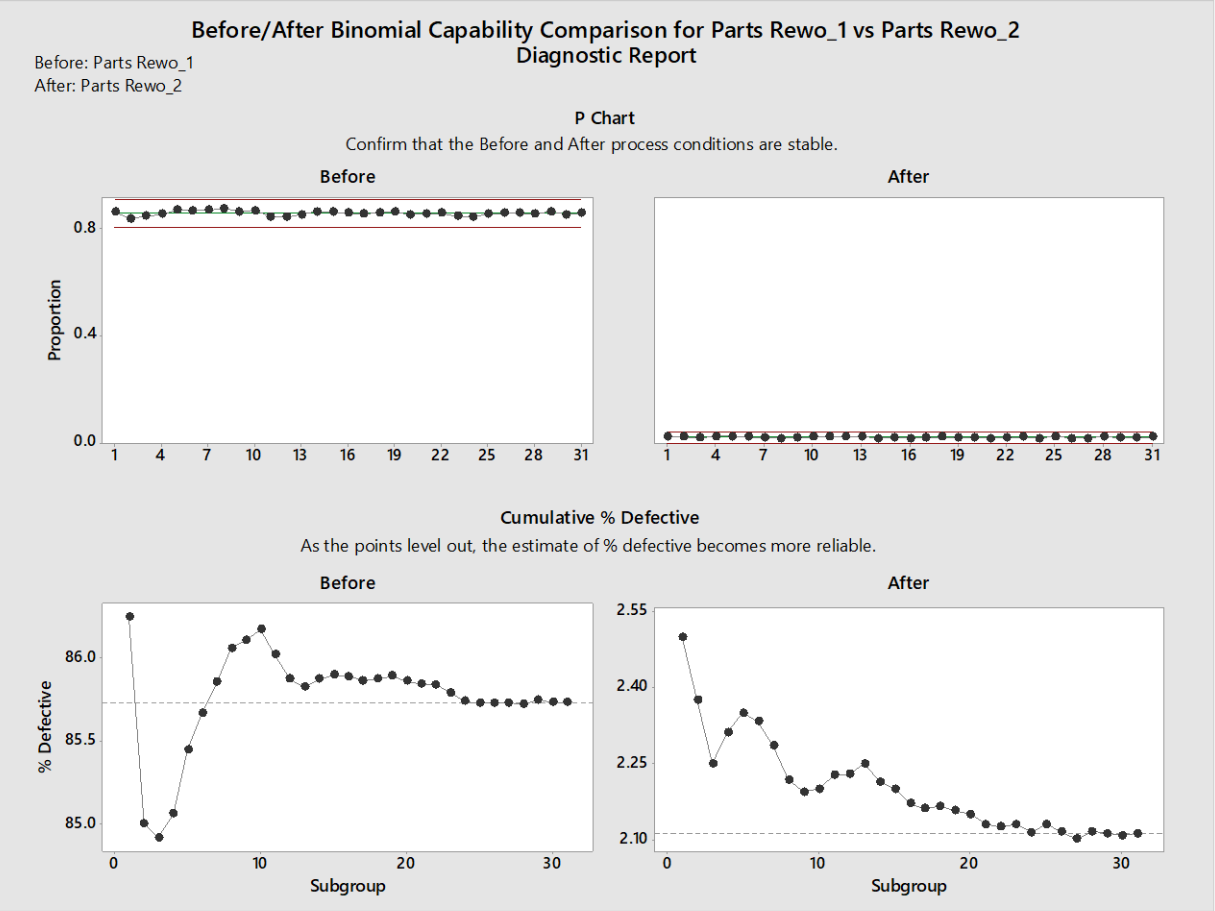

Figure 4.3 Before Vs After improvement comparison of painting activity

Graphs above show the P-Chart and Cumulative % defect charts for before and after the improvements done. It can be observed in the P-Chart that the defect rate was within the 0.8 to 1.0 range while after improvement the range was narrowed drastically and came withing 0.01 to 0.03 defect rate. The cumulative % defect graph shows that before the improvement, the points gradually level out to near 85.7-85.8% while after improvement the points gradually level out to near 2.1% of defect rate which further validates our improvement.

4.3 CONTROL

Now when the results were validated, it is necessary to control the findings through system hence, the material was changed in Bill of Materials (BOM) through BOM Change Request Form (BCRF) raised by the engineering department which was further approved by all stakeholders of this firm. This further reduced the cost of plastic part and hence bringing some reduction in overall product cost of Water Dispenser.

CHAPTER 5
CONCLUSION AND FUTURE WORK

5.1 CONCLUSION

After going through the initial problem and the course of study along with analysis of our trials and experiments, the following conclusions were made:

- **Baking temperature** is a **non-significant factor** and is to be kept at **60°C**
- **Use of IPA** is a **significant factor** and should **not be used**
- **Use of thinner** in paint solution is a **non-significant factor** and is **to be used** when making paint mixture
- **Materia**l used for plastic parts is a **significant factor** and was concluded as **ABS White**

IPA (Iso-propyl Alcohol or Isopropanol) is used for cleaning part surface as a degreasing agent and contains 70-80% of alcohol which attacks the areas near injection points having residual stresses. Due to high density of alcohol, it must not be used before application of paint.

5.2 FUTURE RESEARCH

Future work for this research can be exploring the areas of working on injection molding parameters or doing a material flow analysis inside the mold to find the exact areas being affected by residual stresses and making the required modification in molds after carrying out a detailed study on behavior of mold and material.

REFERENCES

[1] H. M. Beheshti, "Gaining and sustaining competitive advantage with activity based cost management system," *Industrial Management & Data Systems.,* 2004.

[2] S. Silva, J. C. Sa, F. G. Silva, L. P. Ferreira and G. Santos, "Lean Green—The importance of integrating environment into lean philosophy - A Case Study," in *Proceedings of the 6th European Lean Educator Conference*, 2019.

[3] S. N. Telli, V. S. Majali, U. M. Bhushi and V. G. Surange, "Impact of poor quality cost in automobile industry," *International Journal of Quality Engineering and Technology,* vol. 4(1), pp. 21-41, 2014.

[4] M. O. George, The lean six sigma guide to doing more with less: cut costs, reduce waste, and lower your overhead, John Wiley & Sons, 2010.

[5] V. E. Sower, R. Quarles and E. Broussard, "Cost of quality usage and its relationship to quality system maturity," *International Journal of Quality & Reliability Management,* vol. 24(2), pp. 121-140, 2007.

[6] A. Schiffauerova and V. Thomson, "Managing cost of quality: insight into industry practice," *The TQM Magazine,* vol. 18(5), pp. 542-550, 2006.

[7] D. Hoyle, Quality management essentials, Routledge, 2007.

[8] ASQ, "American Society for Quality," 2023. [Online]. Available: https://asq.org/quality-resources/cost-of-quality.

[9] A. Schiffauerova and V. Thomson, " A review of research on cost of quality models and best practices," *International Journal of Quality & Reliability Management.,* 2006.

[10] J. J. Plunket and B. G. Dale, "A review of the literature on quality-related costs," *International Journal of Quality & Reliability Management,* vol. 4(1), pp. 40-52, 1987.

[11] K. Suzaki, New manufacturing challenge: Techniques for continuous improvement, Simon and Schuster, 1987.

[12] D. Setijono, The Development of Quality Management toward Customer Value Creation, Diss. Växjö University Press, 2008.

[13] K. C. Lee and B. Choi, "Six Sigma management activities and their influence on corporate competitiveness," *Total Quality Management & Business Excellence,* vol. 17, no. 7, pp. 893-911, 2006.

[14] R. Caulcutt, "Why is Six Sigma so successful?," *Journal of Applied Statistics,* vol. 28, no. 3-4, pp. 301-306, 2001.

[15] J. Ravichandran, "A review of specification limits and control limits from the perspective of Six Sigma quality processes," *International Journal of Six Sigma and Competitive Advantage,* vol. 11, no. 1, pp. 58-72, 2019.

[16] G. H. Watson and C. F. DeYong, "Design for Six Sigma: caveat emptor," *International Journal of Lean Six Sigma,* vol. 1, no. 1, pp. 66-84, 2010.

[17] M. Uluskan, "A comprehensive insight into the Six Sigma DMAIC toolbox," *International Journal of Lean Six Sigma,* vol. 7, no. 4, pp. 406-429, 2016.

[18] A. Tenera and L. C. Pinto, "A Lean Six Sigma (LSS) project management improvement model," *Procedia-Social and Behavioral Sciences,* vol. 119, pp. 912-920, 2014.

[19] A. Ishak, K. Siregar and H. Naibaho, "Quality control with Six Sigma DMAIC and grey failure mode effect anaysis (FMEA): a review," in *IOP Conference Series: Materials Science and Engineering*, 2019.

[20] S. Ranga and M. Jaimini, "A review on Design of Experiments (DOE)," *Int. J. Pharm. Chem. Sci,* vol. 3(1), pp. 216-224,

2014.

[21] B. Durakovic, "Design of experiments application, concepts, examples: State of the art," *Periodicals of Engineering and Natural Sciences,* vol. 5(3), 2017.

[22] K. Srinivasan, S. Muthu, R. S. Devadasan and C. Sugumaran, "Six Sigma through DMAIC phases: a literature review," *International Journal of Productivity and Quality Management,* vol. 17(2), pp. 236-257, 2016.

[23] A. Emrouznejad and E. Thanassoulis, Introduction to performance improvement management software (PIM-DEA), IGI Global, 2014.

[24] B. J. Singh and D. Khanduja, "Perspectives of control phase to manage Six Sigma implements: an empirical study," *International Journal of Business Excellence,* vol. 7(1), pp. 88-111, 2014.

[25] A. Prashar, "Adoption of Six Sigma DMAIC to reduce cost of poor quality," *International Journal of Productivity and Performance Management,* vol. 63(1), pp. 103-126, 2014.

[26] A. Ardalan, J. Hammesfahr and J. Pope, "Total quality control: the repair facility," *Industrial Management & Data Systems,* vol. 92(8), pp. 7-10, 1992.

[27] D. V. Rosato and M. G. Rosato, Injection molding handbook, Springer Science & Business Media, 2012.

[28] B. A. Olmsted and M. Davis, Practical injection molding, CRC Press, 2001.

[29] D. P. Howe, R. Mcllhagger and P. McDonagh, "Potential cost savings in a plastics injection moulding shop," *Journal of Materials Processing Technology,* vol. 26(2), pp. 237-244, 1991.

[30] A. Akbarzadeh and M. Sadeghi, "Parameter study in plastic injection molding process using statistical methods and IWO algorithm," *International Journal of Modeling and Optimization,* vol. 1(2), p. 141, 2011.

[31] T. Jaruga and E. Bociaga, "Visualization of melt flow lines in injection moulding," *Journal of Achievements in Materials and Manufacturing Engineering,* vol. 18, pp. 1-2, 2006.

[32] D. Mathivanan, M. Nouby and R. Vidhya, "Minimization of sink mark defects in injection molding process–Taguchi approach," *International Journal of Engineering, Science and Technology,* vol. 2(2), pp. 13-22, 2010.

[33] A. A. Dzulkipli and M. Azuddin, "Study of the effects of injection molding parameter on weld line formation," *Procedia engineering,* vol. 184, pp. 663-672, 2017.

[34] M. Moayyedian, K. Abhary and R. Marian, "The analysis of short shot possibility in injection molding process," *The International Journal of Advanced Manufacturing Technology,* vol. 91, pp. 3977-3989, 2017.

[35] S. C. Nian, C. Y. Wu and M. S. Huang, "Warpage control of thin-walled injection molding using local mold temperatures," *International Communications in Heat and Mass Transfer,* vol. 61, pp. 102-110, 2015.

[36] W. B. Noon, "Industrial Painting Techniques," *Product Treatment & Finishing,* pp. 143-150, 1972.

[37] J. Puetz and M. A. Aegerter, "Dip coating technique," *Sol-gel technologies for glass producers and users,* pp. 37-48, 2004.

[38] E. B. Gutoff and E. D. Cohen, "Water-and solvent-based coating technology," William Andrew Publishing, 2016.

[39] S. Poozesh, N. Akafuah and K. Saito, "Effects of automotive paint spray technology on the paint transfer efficiency–a review," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering,* vol. 232(2), pp. 282-301, 2018.

[40] R. L. Hines, "Electrostatic atomization and spray painting," *Journal of Applied Physics,* vol. 37(7), pp. 2730-2736, 1966.

[41] M. W. Plesniak, P. E. Sojka and A. K. Singh, "Transfer efficiency for airless painting systems," *JCT research,* vol. 1, pp. 137-145, 2004.

[42] G. W. Thompson, "Painting Defects: Their Causes and Prevention," *Industrial & Engineering Chemistry,* vol. 7(2), pp. 136-145, 1915.

[43] X. Jin, W. Bi and H. Qian, "Root cause analysis of pinhole defects on painted galvanized steel panel," *Engineering Failure Analysis,* vol. 115, p. 104598, 2020.

[44] F. Giorgiutti-Dauphiné and L. Pauchard, "Painting cracks: A way to investigate the pictorial matter," *Journal of Applied Physics,* vol. 120(6), p. 065107, 2016.

[45] P. L. Evans, L. W. Schwartz and R. V. Roy, "A mathematical model for crater defect formation in a drying paint layer," *Journal of colloid and interface science,* vol. 227(1), pp. 191-205, 2000.

[46] C. K. Schoff, "Painting Problems," in *Coatings of Polymers and Plastics*, CRC Press, 2003, pp. 200-238.

[47] J. C. Love, G. F. Smith, M. Pharaoh and R. Coates, "Orange peel: Who cares?," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering,* vol. 125(12), pp. 1241-1244, 2001.

[48] "HOME APPLIANCES MARKET SIZE & SHARE ANALYSIS - GROWTH TRENDS & FORECASTS," Mordorintellgience. [Online].

[49] S. Mahmood, S. M. Ahmed and K. Panthi, "Determining the cost of poor quality and its impact on productivity and profitability," *Built Environment Project and Asset Management,* vol. 4(3), pp. 296-311, 2014.

[50] O. M. Ikumapayi, E. T. Akinlabi, F. M. Mwema and O. S. Ogbona, "Six sigma versus lean manufacturing–An overview," *Materials Today: Proceedings,* vol. 26, pp. 3275-3281, 2020.

[51] P. M. Madhani, "Lean Six Sigma deployment in retail industry: enhancing competitive advantages," *The IUP Journal of Business Strategy,* vol. 17(3), pp. 25-45, 2020.

[52] P. Rewers and J. Trojanowska, "Tools and methods of Lean Manufacturing-a literature review," in *Proceedings of 7th international technical conference technological forum*, 2016.

[53] B. R. Krishnan and K. A. Prasath, "SIX SIGMA CONCEPT AND DMAIC IMPLEMENTATION," *International Journal of Business Management & Research (IJBMR) ,* vol. 3(2), pp. 111-114, 2013.

[54] S. N. Teli, V. S. Majali and U. M. Bhushi, "Cost of poor quality analysis for automobile industry: a case study," *Journal of The Institution of Engineers (India),* vol. C(94), pp. 373-384, 2013.

[55] S. N. Teli, V. S. Majali, U. Bhushi and V. Surange, "Assessment of Cost of poor quality for Automobile Industry," *International Journal of Engineering Research and Applications,* vol. 2(6), pp. 330-336, 2012.

[56] C. Fernandes, A. J. Pontes, J. C. Viana and A. Gasper-Cunha, "Modeling and Optimization of the Injection-Molding Process: A Review," *Advances in Polymer Technology,* vol. 37(2), pp. 429-449, 2018.

[57] L. Tredoux, I. Satoh and Y. Kurosaki, "Investigation of wavelike flow marks in injection molding: A new hypothesis for the generation mechanism," *Polymer Engineering & Science,* vol. 40(10), pp. 2161-2174, 2000.

[58] D. Palmer, "Understanding the Effects of Paint On Plastics," *Plastics Technology,* 2014.

[59] E. Raynaud, E. Darque-Ceretti, B. Monasse, P. Duquesne and F. Georgi, "Visual defects of painted surfaces on ABS/PC injected parts," *MATERIALS & SENSATIONS,* 2008.

[60] D. Palmer, "Effects of Painting on the Mechanical Properties of Injection-Molded Plastics," in *Annual Technical Conference - ANTEC*, 2014.

[61] H. Kaid, M. A. Noman, E. A. Nasr and M. Alkahtani, "Six Sigma DMAIC phases application in Y company: A case study," *International Journal of Collaborative Enterprise,* Vols. 5(3-4), pp. 181-197, 2016.

[62] S. L. Mok and C. K. Kwong, " Application of artificial neural network and fuzzy logic in a case-based system for initial process parameter setting of injection molding," *Journal of Intelligent Manufacturing,* vol. 13, pp. 165-176, 2002.

[63] M. Stanek, D. Manas and M. Manas, "Optimization of injection molding process," *International Journal of Mathematics and Computers in Simulation,* 2011.

[64] Polyplastics, [Online]. Available: https://www.polyplastics.com/en/support/mold/outline/.

[65] "fishbone diagram (Ishikawa cause and effect)," Techtarget, [Online]. Available: https://www.techtarget.com/whatis/definition/fishbone-diagram.

[66] S. Rana and R. M. Belokar, "Quality improvement using FMEA: A short review," *International Research Journal of Engineering and Technology,* vol. 4(6), pp. 263-267, 2017.

[67] S. K., "Failure mode and effect analysis (FMEA) of pipeline ball valves in the offshore industry," *Journal Of Failure*

Analysis And Prevention, vol. 20, no. 4, pp. 1175-1183, 2020.

[68] "FMEA (Failure Mode and Effects Analysis) Quick Guide," Isixsigma, [Online]. Available: https://www.isixsigma.com/uncategorized/fmea-quick-guide/.

[69] "Cost of Quality: Not Only Failure Costs," isixsigma, [Online]. Available: https://www.isixsigma.com/financial-analysis/cost-quality-not-only-failure-costs/.

[70] "Cost of Poor Quality (COPQ)," isixsigma, [Online]. Available: https://www.isixsigma.com/dictionary/cost-of-poor-quality-copq/.

[71] Polyplastics, [Online]. Available: https://www.polyplastics.com/en/support/mold/outline/.

[72] "7 common injection molding defects and how to avoid them," Fast Radius, [Online]. Available: https://www.fastradius.com/resources/injection-molding-defects/.

[73] Dawlance, [Online]. Available: https://www.dawlance.com.pk/water-dispensers.