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Reducing Bottle Height Variation to Enhance Quality, Operational Efficiency, and Revenue

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Abstract

In the pursuit of quality excellence within high-speed manufacturing, this study applies Six Sigma methodology to minimize bottle height variation in the production line of XYZ Company. The existing process exhibited noticeable deviations in bottle height, contributing to critical quality issues such as improper capping, fluid filling inaccuracies, and instability ultimately leading to increased rework, customer dissatisfaction, and loss of revenue. This research targets a reduction of height variation through a data-driven approach grounded in the DMAIC framework.

During the Measure phase, baseline performance was assessed using historical production data and statistical tools to evaluate current process behavior. The analysis revealed a high degree of variation and significant misalignment with quality standards, indicating that the existing process is incapable of consistently meeting specifications. The distribution of data also exhibited asymmetry, suggesting systemic issues affecting process stability. These insights emphasize the urgent need for process improvements to reduce variability and enhance manufacturing precision.

This project serves as a foundational benchmark in developing sustainable quality interventions in subsequent phases. The results underscore the critical role of data validation and process capability analysis in identifying root causes of variation. By reducing height inconsistency, the study not only aims to elevate first-pass yield and operational efficiency but also supports long-term customer satisfaction and business sustainability.

Keywords
Six Sigma, Process Capability, DMAIC, Manufacturing Quality, Statistical Process Control

1. Introduction
In today's competitive manufacturing landscape, maintaining high-quality standards is essential to ensuring product consistency and customer satisfaction. At XYZ, the current bottle manufacturing process exhibits an average height variation of 0.19mm, leading to significant quality concerns. These variations result in instability, tipping risks, improper capping, and inaccurate fluid filling, which not only affect operational efficiency but also increase rework and customer dissatisfaction. This Define Phase report aims to systematically address these issues using the Six Sigma methodology. By clearly defining the problem, its impact, and key project goals, this report sets the foundation for a data-driven approach to improving process stability, reducing defects, and enhancing overall business performance.

1.1. Problem Statement
The current PET (Polyethylene Terephthalate) bottle manufacturing process at XYZ shows an average height variation of 0.19 mm, leading to issues like tipping, improper capping, and inaccurate filling. These defects cause rework, waste,

and customer dissatisfaction, ultimately affecting product quality and business performance. Reducing this variation is essential for maintaining efficiency and reliability in high-speed PET bottle production.

1.2. Objective
The objective of this project is to reduce bottle height variation in XYZ Company's PET (Polyethylene Terephthalate) bottle manufacturing process by applying the Six Sigma DMAIC framework. Through data-driven analysis and systematic problem-solving, the project aims to identify root causes of dimensional inconsistency and implement targeted improvements that enhance product quality, improve operational efficiency, and support long-term customer satisfaction. Ultimately, this initiative seeks to build a stable and capable process that minimizes defects, reduces rework, and contributes to overall business performance.

2. Literature Review
The Six Sigma methodology, particularly the DMAIC framework, has been widely adopted across industries to reduce process variation and improve quality outcomes. As defined by Antony (2023), Six Sigma is a structured, data-driven approach that applies statistical methods to identify and eliminate defects in manufacturing and service processes. The DMAIC cycle Define, Measure, Analyze, Improve, and Control provides a disciplined framework that ensures continuous quality improvement through root cause identification and evidence-based corrective action.

The efficacy of Six Sigma in manufacturing settings has been shown in numerous research. By identifying important process factors, Mittal et al. (2023), for instance, successfully decreased product rejection rates in an Indian manufacturing company using the DMAIC framework. Similarly, in order to eliminate polypropylene bag faults, Sajjad et al. (2021) used Six Sigma and came to the conclusion that data-driven experimentation was crucial for determining the best process parameters. Ullah et al. (2016) conducted a case study in a PET bottle manufacturing company and highlighted the importance of resin type, injection pressure, and melting temperature in impacting defect rates. These findings are in line with their research. The importance of design of experiments (DOE) in process setting optimization was also emphasized by their study. Quantifying baseline performance and determining whether a process can fulfil customer criteria are common uses for process capability analysis, a key tool in the Measure phase (Montgomery, 2019). According to other studies that use JMP software for exponential and Johnson distributions, non-normal data distributions in this context necessitate proper statistical management (Peruchi et al., 2020). Practitioners can assess process stability even in cases when the data deviates from normalcy thanks to these methodologies.

In order to proactively evaluate possible failure points and rank corrective measures, risk mitigation techniques such as Failure Modes and Effects Analysis (FMEA) are incorporated into the Improve phase. Both the manufacturing (Antony et al., 2016) and service (Antony et al., 2022) sectors have shown improvement in critical-to-quality faults through the use of fishbone diagrams and 5 Whys analysis for root cause diagnosis.

The use of Six Sigma as a strong approach for increasing process capability, decreasing faults, and improving product consistency is supported by the body of available research taken together. Building on this foundation, the current project uses DMAIC methods like DOE (Antony 2023), FMEA, process capability analysis, and SPC to target dimensional variation in bottle height, a recurrent fault in high-speed PET bottle manufacturing.

3. Methodology
This project was conducted using the Six Sigma methodology, a data-driven approach to process improvement that seeks to eliminate defects and reduce variation. Six Sigma provides organizations with tools to improve the capability of their business processes (Zu et al. 2008). It emphasizes the use of statistical analysis and structured problem-solving to achieve measurable results.

At the core of Six Sigma is the DMAIC framework, which stands for Define, Measure, Analyze, Improve, and Control. This structured approach was applied throughout the project to investigate and reduce variation in bottle height during manufacturing. Each phase of DMAIC guided specific activities, data collection, and analysis, ensuring a systematic path toward sustainable process improvement.

4. Results and Discussion

4.1. Define Phase

The Define phase focused on identifying the problem, setting project goals, and understanding customer requirements (CTQs – Critical to Quality). In this case, the primary concern was excessive variation in bottle height, which led to inconsistency and quality issues in packaging. A SIPOC diagram was developed to map the overall process and identify key stakeholders, while a project charter was created to define the scope, timeline, and objectives (Figure 1 and 2).

Project Charter

Height in variation in Bottle Manufacturing

Problem Statement

The current PET (Polyethylene Terephthalate) bottle manufacturing process at XYZ shows an average height variation of 0.19 mm, leading to issues like tipping, improper capping, and inaccurate filling. These defects cause rework, waste, and customer dissatisfaction, ultimately affecting product quality and business performance. Reducing this variation is essential for maintaining efficiency and reliability in high-speed PET bottle production.

Business Case & Benefits

Reducing the current average bottle height variation from 0.19mm to less than 0.1mm is essential to preventing instability, capping defects, and fluid inaccuracies, which impact efficiency, customer satisfaction, and revenue. Addressing this issue now will minimize defects, lower costs of operations, and mitigate reputational risks while supporting business goals of quality improvement, waste reduction, and increased profitability.

Goal Statement

The goal is to reduce PET bottle height variation from 0.19 mm to below 0.1 mm within three months.

Timeline

Phase	Planned Completion Date	Actual
Define:	18-Feb	20-Feb
Measure:	15-Mar	7-Mar
Analyze:	10-Apr	11-Apr
Improve:	25-Apr	25-Apr
Control:	5-May	2-May

Scope - First/Last and In/Out

1st Process Step	Preforms go into hopper
Last Process Step	Well Shaped bottles come in outfit conveyor
In Scope	Plastic particles, moulds, machines, Blow moulding process(heating and cooling), New Staff
Out Of Scope	Liquid which is going to be in the bottle, Production scedules.

Indicator

Indicator (Measure)	Average height difference(in MM)

Team Members

Position	Person	Title	% of Time
Team Lead	Chhayank Bhirud	Team Leader	33%
Sponsor	XYZ	Company Employee	
Team Member	Akash Toradmal	Member	33%
Team Member	Chirag Poshirkar	Member	33%

Figure 1: Project Charter

SUPPLIER (S)	INPUTS (I)	PROCESS (P)	OUTPUTS (O)	CUSTOMER (C)
• Plastic Preforms Supplier. • Machinery and Equipment Supplier. • Chemical Supplier.	• Preforms • Energy(electricity) • Coolant • Skilled Workforce • Quality Inspectors and technicians. • Quality control Tools	• Preforms are loaded into a Hopper. • Heated in preheater 1 and 2 for softening. • Expanded into a basic bottle shape in the pre-mold station. • Transferred to the final mold for the finished shape. • Coolant circulates around the mold for rapid cooling. • Bottle is ejected and moved via conveyor for inspection.	• Quality plastic bottles • Rejected Bottles • Quality Reports	• Quality Control Department

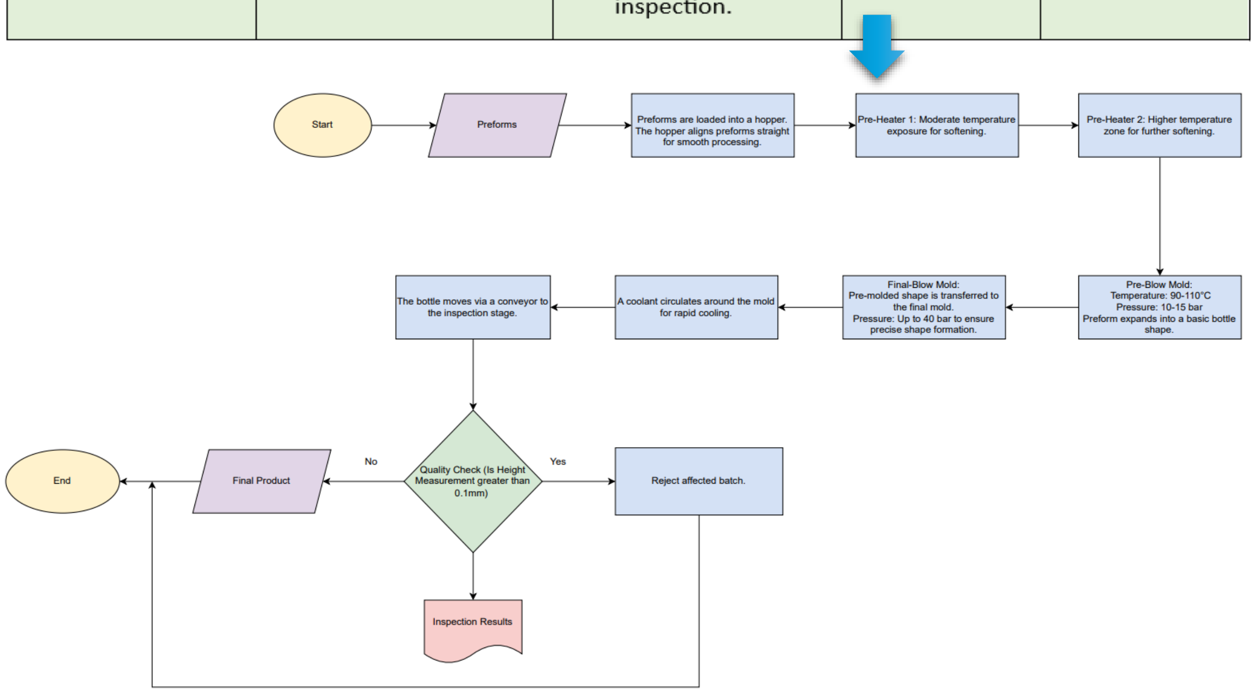


Figure 2: SIPOC diagram detailing inputs, outputs, and key focus areas for Bottle Manufacturing

4.2. Measure Phase

The Measure phase in the Six Sigma DMAIC (Define, Measure, Analyze, Improve, Control) process is focused on quantifying the problem. Here, you aim to establish baseline metrics and evaluate the current process performance. For your project aimed at reducing the Bottle height variance for XYZ company, the Measure phase involves:

- Defining Key Metrics: Bottle height (i.e. High value and Low value)
- Collecting Baseline Data: Establishing the current performance levels and gathering data that can serve as a benchmark. This baseline is essential for comparing improvements as changes are implemented.
- Validating Data Collection: Ensuring the data is accurate, complete, and reliable. This can involve data cleansing and verification processes.

Data Collection Plan

The data collection aimed to support the project goal of reducing bottle height variance below 0.1 mm by establishing a reliable performance baseline and quantifying defect levels. This aligns with Six Sigma's objective of minimizing variation to improve process control and customer satisfaction. Key variables included high and low bottle height values, with height difference (in mm) as the output. The data, continuous in nature, was sourced from company production records maintained by the Quality Control (QC) team. A targeted sampling strategy focused on the most defective cases over the past six months. Daily data collection over this period ensured a robust dataset. Microsoft Excel was used for initial organization, while JMP handled statistical analysis. The QC team collected and logged the data, with the QC Supervisor managing data access and verification; analysis was conducted by the Six Sigma project team.

	A	B	C
1	Cavity #3 - Bottle Height - HIGH Value	Cavity #3 - Bottle Height - LOW Value	Cavity #3 - Height Difference
2	229.24	229.22	0.02
3	229.24	229.02	0.22
4	229.88	229.79	0.09
5	229.47	229.11	0.36
6	229.66	229.53	0.13
7	229.03	228.98	0.05
8	229.55	228.88	0.67
9	230.22	230.07	0.15

Figure 3: Presents the sample dataset used in our project

The Figure 3 is the data set used in measure phase. Column A (Bottle Height- High Value), Column B (Bottle Height- Low Value) and Column C (Height Difference). To establish baseline process performance, data were collected from all seven cavities involved in bottle production. Cavity 3 was selected for in-depth analysis as it demonstrated the highest degree of height variation among all cavities. A total of 116 observations were recorded over a six-month period, capturing the maximum and minimum bottle heights for each cycle. The resulting height differences ranged from 0.00 mm to 1.47 mm, indicating substantial dimensional variability. This dataset served as the foundation for process capability assessment and subsequent root cause analysis within the DMAIC framework.

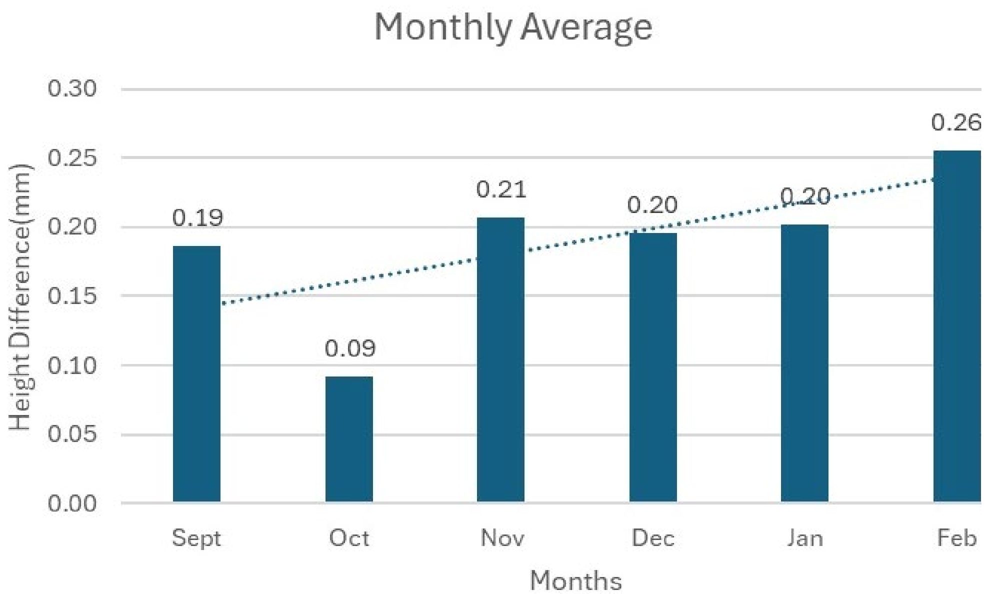
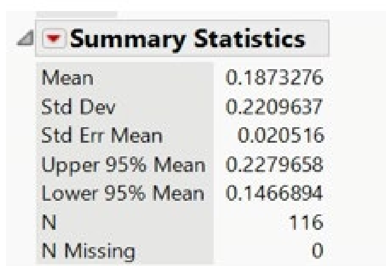


Figure 4: Monthly Average height difference observed in Cavity 3 over a six-month period

Figure 4 shows Monthly Average height difference observed in Cavity 3 over a six-month period. The data reveals a clear upward trend in bottle height variation, beginning at 0.19 mm in September, dipping to a low of 0.09 mm in October, and steadily increasing to a peak of 0.26 mm in February. This consistent rise in variation over time suggests a progressive decline in process stability and indicates that underlying issues have either worsened or remained unaddressed. The trendline reinforces this escalation, highlighting a gradual but concerning shift away from acceptable tolerance levels. These findings underscore the urgent need for root cause analysis and corrective actions to bring the process back within desired specification limits and ensure long-term dimensional consistency in production.
Descriptive statistics were calculated utilizing the statistical analysis software, JMP. The data, extracted and formatted to a csv file, was uploaded to JMP and the descriptive statistics were computed (Figure 3).



Summary Statistics

Mean	0.1873276
Std Dev	0.2209637
Std Err Mean	0.020516
Upper 95% Mean	0.2279658
Lower 95% Mean	0.1466894
N	116
N Missing	0

Figure 5: Descriptive statistics calculated using JMP

Figure 5 shows the summary statistics for height difference in Cavity 3. The mean height variation is 0.197 mm, which exceeds the project goal of 0.1 mm, indicating poor process performance. A standard deviation of 0.221 mm reflects high variability, and the 95% confidence interval (0.147 mm to 0.228 mm) confirms that the average variation consistently falls outside the acceptable range. These findings highlight the need for immediate process improvement.

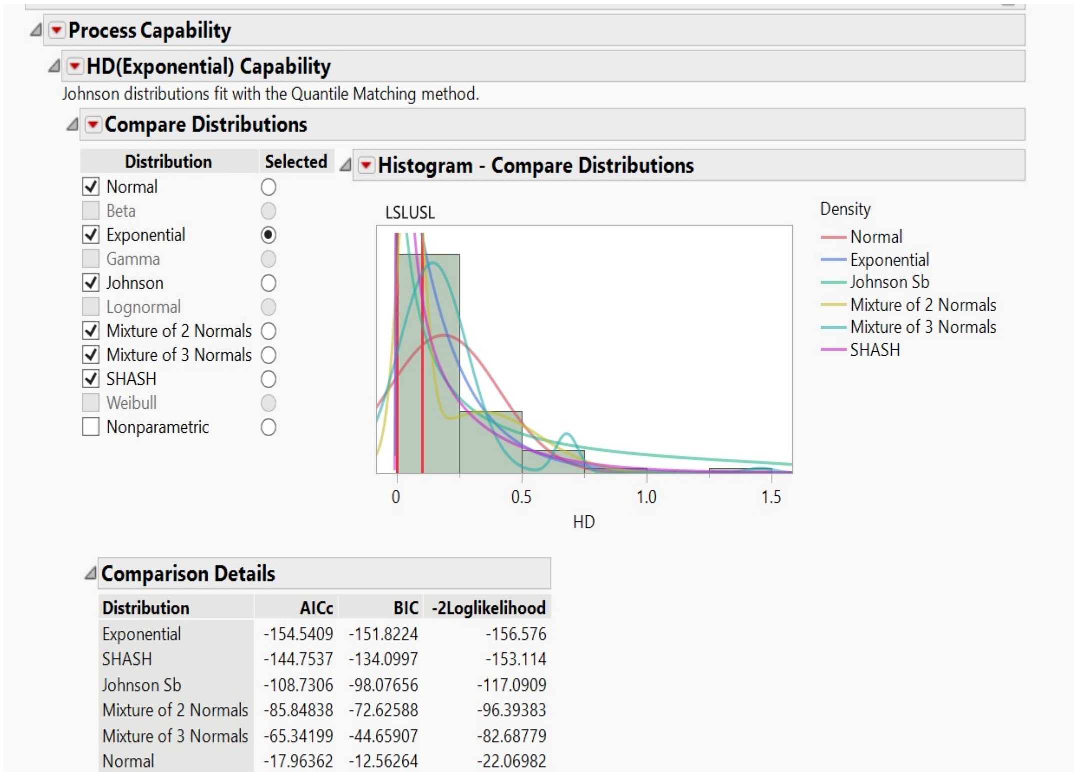


Figure 6: Process capability analysis performed in JMP software.

Figure 6 displays the distribution fitting results for bottle height difference (HD), comparing several statistical models to determine the most appropriate fit for the data. Based on the AIC, BIC, and log-likelihood values shown in the Comparison Details table, the Exponential distribution provided the best fit, followed closely by the SHASH and Johnson Sb distributions. The histogram and density curves confirm that the data is non normal, with a long right tail and skewness. These findings justify the use of non-normal capability analysis methods (Peruchi et al. 2020) for evaluating process performance, as normality assumptions do not hold for this dataset.

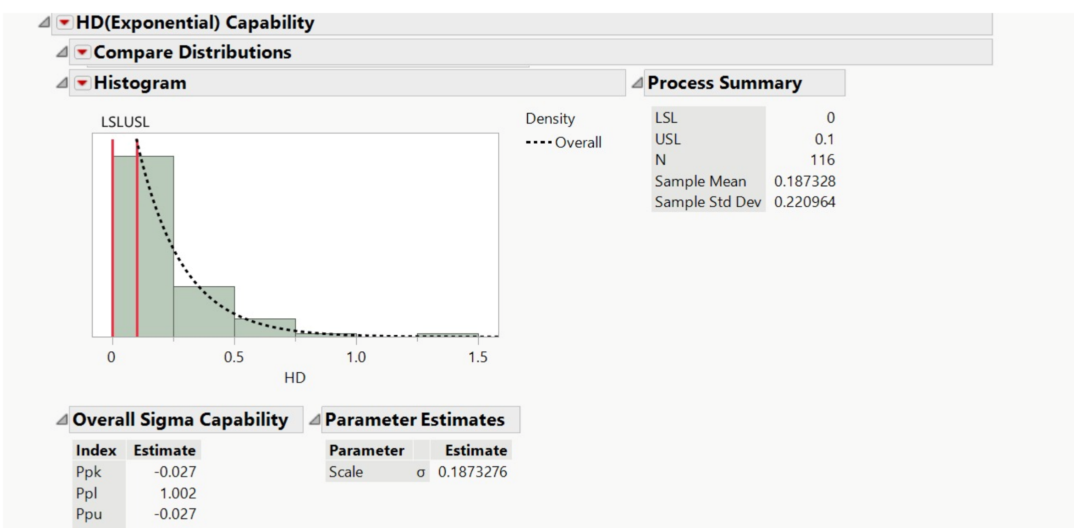


Figure 7: Process capability analysis for bottle height difference using an exponential distribution model

Figure 7 process capability analysis for bottle height difference using an exponential distribution model. The USL was set at 0.1 mm, aligning with the project's specification target, while the sample mean was 0.197 mm with a standard deviation of 0.221 mm. The process performance indices indicate poor capability, with Ppk = -0.027, confirming that the process mean lies outside the acceptable limits. Additionally, 51.72% of the observations exceeded the USL, reflecting significant nonconformance. These findings verify that the current process is not capable of meeting quality standards and underscores the need for corrective action to reduce variation and shift the process mean closer to the target.

4.3. Analyze Phase

The Analyze phase focused on identifying and validating the root causes of bottle height variation. A structured root cause analysis was conducted using several quality tools: A Fishbone (Ishikawa) diagram (Antony et al. 2016) was used to categorize and visualize potential sources of variation across areas such as machinery, materials, methods, environment, and manpower.

The 5 Whys technique (Antony et al. 2022) was applied to drill down into each major cause identified in the Fishbone diagram, helping to uncover underlying issues rather than just surface-level symptoms. This combination of tools enabled a comprehensive understanding of how different factors contributed to the variation and helped prioritize the most critical areas for improvement.

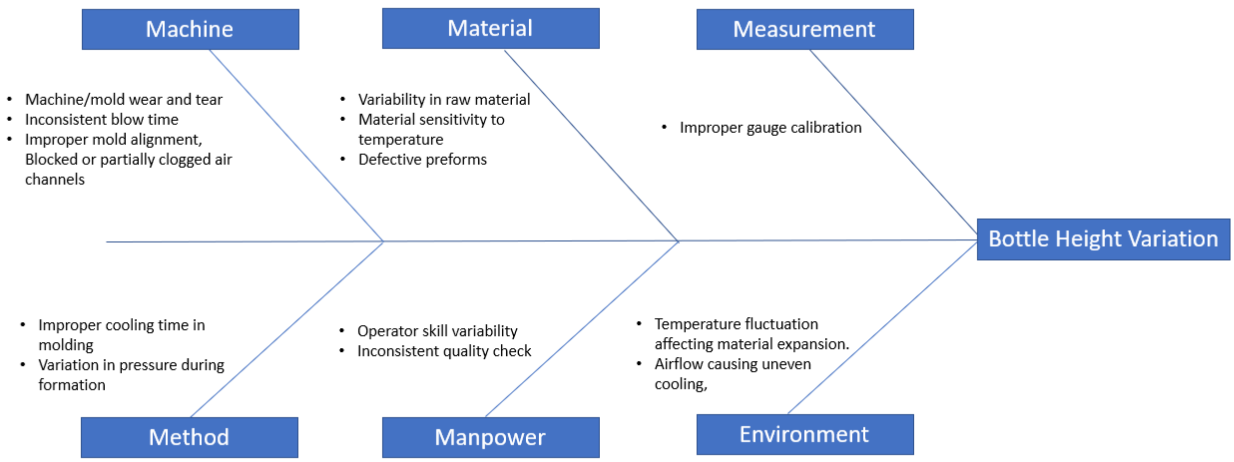


Figure 8: Fishbone, or Ishikawa, diagram for brainstorming potential causes for Bottle Manufacturing

Figure 8 shows a Fishbone (Ishikawa) diagram used to systematically identify root causes of bottle height variation. Causes are grouped into six categories: Machine, Material, Measurement, Method, Manpower, and Environment. Key machine-related issues included mold wear, inconsistent blow time, misalignment, and blocked air channels. Material factors involved raw material variability, temperature sensitivity, and defective preforms. Measurement concerns focused on uncalibrated gauges, while method issues included inconsistent cooling time and pressure. Manpower-related causes involved varying operator skill and inconsistent checks. Environmental factors like temperature changes and uneven airflow also affected molding. This structured analysis supported root cause identification and prioritized corrective actions in the Analyze phase.

Brainstorming Results: To identify the root cause of "Bottle height variation", we used the Five Whys methodology.

5 Whys Analysis:

- **Problem: Inconsistent Bottle Height Due to Blow Time Variability**
- **Why is the bottle height inconsistent?**

Because the blow time during bottle forming varies, which affects how much the bottle expands.

- **Why does the blow time vary?**

Because the machine is programmed with a blow time range of 1.5 to 1.9 seconds.

- **Why is there such a wide range (0.4 seconds)?**

Because the machine manufacturer recommended this general range, but it was not optimized for this specific bottle design or material.

• **Why hasn't the blow time been optimized for our specific process?**
Because no process study or DOE (Design of Experiments) has been conducted to determine the ideal blow time that minimizes variation.
• **Why hasn't a process study been conducted?**
Because there was an assumption that the manufacturer-recommended settings were sufficient, and no continuous improvement initiative was in place to fine-tune the parameters.
Root Cause: Lack of process-specific optimization for blow time the factory is using a broad manufacturer-specified range (1.5–1.9 sec) without validating the ideal setting through data-driven experimentation.
Root Cause: Limited inspection scope and incomplete feedback integration between departments have led to occasional oversight of defective preforms, despite having a quality control team.
The 5 Whys Analysis revealed three main root causes of bottle height variation. First, blow time variability stemmed from using a broad manufacturer-recommended range (1.5–1.9 seconds) without optimization, due to the lack of DOE or continuous improvement. Second, irregular gauge calibration led to inaccurate measurements, caused by undocumented procedures and a reactive quality approach. Third, defective preforms entered production because of limited inspection scope and weak coordination between quality, production, and procurement. These issues point to major gaps in process control, preventive maintenance, and interdepartmental communication.

4.4. Improve Phase

The Improve phase of the DMAIC process focused on designing and testing effective solutions to address the root causes identified earlier. For the XYZ bottle manufacturing process, the team used brainstorming sessions, prioritization tools, and pilot implementation planning to drive sustainable improvement. The key issues included unoptimized blow time due to a broad range (1.5–1.9 sec), irregular calibration from a lack of scheduled maintenance, and defective preforms resulting from limited inspection criteria.

To address these, the team proposed a Design of Experiments (DOE) to determine optimal blow time (Khan et al. 2014; Antony 2023), implementing a routine calibration schedule, expanding dimensional checks during incoming inspections, introducing automated in-line measurement systems, and enhancing communication between Quality, Production, and Procurement teams. A Weighted Decision Matrix was used to prioritize these solutions based on effectiveness, feasibility, cost, and sustainability, with each rated on a scale of 1 to 5.

Table 1: Weighted matrix used to prioritize solution

Solution	Easy to Implement (3)	Quick to Execute (5)	High Impact (9)	Cost (9)	Total Score
DOE for Blow Time	3	4	5	4	110
Calibration Schedule	5	5	3	4	103
Expand Preform Inspection	3	3	5	3	96
Real-Time Monitoring	2	2	5	2	79

Table 1 shows the Weighted Decision Matrix used to prioritize solutions for reducing bottle height variation. The DOE for blow time ranked highest (110) as the most impactful and feasible solution, followed by the calibration schedule (103) for its ease and speed of implementation. Preform inspection (96) showed value but required more resources, while real-time monitoring (79) scored lowest due to cost and complexity. DOE and calibration were selected as the most practical solutions.

Testing and Validation (Suggested Pilot Plan)
A pilot study using a one-factor DOE tested blow times of 1.5 to 1.9 seconds, with ANOVA confirming that 1.9 s achieved the lowest height variation (~0.08 mm), meeting the target of <0.1 mm. Alongside, a weekly gauge calibration program was proposed, supported by MSA to ensure measurement reliability and early detection of performance drift.

After validation, full implementation will proceed on two fronts: locking the optimized blow time into machine settings with updated SOPs and training, and formalizing the calibration schedule within the Quality Management System. Rollout is planned over three weeks to minimize disruptions and ensure smooth adoption. An FMEA (Antony et al. 2016) was also conducted to assess risks, identify failure modes, and recommend preventive controls, reinforcing the reliability of the proposed improvements.

Table 2: FMEA Matrix for Improve Phase

Process Step/Component	Failure Mode	Effect	Severity (S)	Cause	Occurrence (O)	Detection (D)	RPN	Recommended Action
Blow Molding - Blow Time	Incorrect blow time setting	Bottle height variation exceeds spec	8	Improper optimization	4	3	96	Lock in optimized blow time via DOE and SOP training
Height Gauge Calibration	Gauge out of calibration	Inaccurate height measurement	7	No routine schedule	3	4	84	Establish weekly calibration schedule and track logs
Incoming Preform Inspection	Defective preforms undetected	Variation introduced in bottle dimensions	6	Inadequate inspection criteria	2	5	60	Expand inspection scope to include dimensional checks

Table 2 summarizes the FMEA conducted during the Improve phase to evaluate risks tied to proposed changes. Three key failure modes were identified: incorrect blow time (RPN 96), undetected defective preforms (RPN 90), and gauge miscalibration (RPN 84). These risks were addressed through DOE for blow time optimization, a routine calibration schedule, and expanded inspection criteria to enhance process reliability.

Overall, the Improve phase offers a structured, data-driven approach to reducing height variation. While not yet implemented, the proposed solutions lay a solid foundation for improving product quality and operational consistency at XYZ.

4.5. Control Phase

The Control phase, the final step in the DMAIC cycle, ensures that improvements are sustained by embedding them into daily operations, monitoring performance, and responding quickly to deviations. This is achieved through structured procedures and data-driven tools to maintain consistent outcomes. To monitor process stability, SPC methods like I-MR charts are recommended for tracking bottle height variation in real time. Control limits based on ±3 standard deviations help identify shifts or special causes early, allowing timely corrective action.

Standardization is essential and includes clear SOPs for blow time, calibration, and inspections, supported by regular training and version-controlled updates. SOPs should be accessible, reviewed periodically, and backed by documentation such as calibration logs and control chart records.A control plan should outline key metrics (e.g., height variation, calibration), review frequency, responsible personnel, and tools like SPC charts or checklists. A strong response plan must include action thresholds, root cause analysis methods (e.g., 5 Whys), CAPA documentation, and escalation protocols. To prevent regression, mistake-proofing (e.g., software locks, calibration alerts) and structured audits (e.g., monthly checklists) help maintain compliance and reinforce continuous quality. This control strategy supports long-term stability and aligns with Six Sigma best practices for reliable adoption at XYZ.

5. Conclusion

This project systematically applied the Six Sigma DMAIC methodology to reduce bottle height variation in the PET (Polyethylene Terephthalate) bottle manufacturing process at XYZ Company. Through rigorous data analysis, root cause identification, and structured problem-solving, key issues such as unoptimized blow time, inconsistent gauge calibration, and inadequate preform inspection were addressed. The proposed improvements including optimized blow time settings and a preventive calibration schedule demonstrated clear potential to enhance dimensional consistency, reduce rework, and improve customer satisfaction. By embedding these changes into standard procedures and establishing robust control mechanisms, XYZ is positioned to achieve sustainable quality improvements and operational efficiency. The study serves as a practical roadmap for future continuous improvement initiatives within high-precision PET bottle manufacturing environments.

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Biographies

Chhayank Bhirud is a graduate student in Engineering Management at California State University, Northridge, with a background in Mechanical Engineering from Vishwakarma Institute of Technology, Pune. He brings practical experience in lean manufacturing, process improvement, and quality control, having led initiatives to enhance efficiency and reduce waste. Chhayank specializes in Six Sigma tools, statistical process control, and data-driven analysis. In this project, he played a key role in identifying sources of process variation and proposing targeted, high-impact improvements. With a strong focus on operational excellence, he aims to drive innovation and performance in modern manufacturing environments.

Akash Toradmal is a graduate student in Engineering Management at California State University, Northridge, with a Bachelor’s in Civil Engineering. He brings a strong blend of analytical skills and hands-on experience in procurement, ERP systems, and supply chain optimization. His projects have focused on cost modeling, supplier evaluation, and process improvement. A state-level cricket player, Akash applies the same discipline and teamwork to his professional endeavors. His recent work involves using the DMAIC framework to reduce dimensional variation in bottle manufacturing, reflecting his commitment to quality and operational excellence.

Chirag Chandrakant Poshirkar is a graduate student in the Master of Science in Engineering Management program at California State University, Northridge. He holds a Bachelor's degree in Mechanical Engineering and has a strong academic interest in quality engineering, process optimization, and data-driven decision-making. Chirag has developed practical skills in Six Sigma methodologies, including the DMAIC framework, statistical process control, and root cause analysis. Through coursework and applied projects, he aims to contribute to operational efficiency and quality improvement in manufacturing and production systems. His long-term goal is to apply these principles in real-world industrial environments to drive continuous improvement and organizational excellence.

Sepideh Abolghasem is an associate professor in the Department of Manufacturing Systems Engineering and Management at California State University at Northridge. Prior to this appointment, she was an associate professor in the Department of Industrial Engineering at the University of Los Andes, Bogotá, Colombia. She earned her B.Sc. degree in Industrial Engineering from Sharif University of Technology, Tehran, Iran and her M.Sc. and Ph.D. degrees in Industrial Engineering from University of Pittsburgh. Her main research interests span the integration of the disciplines of Operations Research and Materials Science. Much of her work has been focused on machining manufacturing process where she tries to improve the understanding of the interrelationships among the process parameters and the microstructure of the materials. Recently, she has been working on the application of machine learning techniques combined with simulation for material properties prediction. She has served as the faculty advisor at IISE and represented Latin America at INFORMS' International Activities Committee.