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Maximizing cleaning efficiency and minimizing rework in a recycling facility using the DMAIC approach

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Abstract
This study applied the DMAIC (Define, Measure, Analyze, Improve, Control) methodology to improve the operational efficiency of a facility's bottle cleaning process. The Define Phase identified critical issues, including a high rework rate (15%), inconsistent cleaning quality (84% efficiency), and excessive water and detergent consumption. The Measure Phase established baseline data to quantify these inefficiencies. Root causes were identified in the Analyze Phase using a Fishbone Diagram and Failure Mode and Effects Analysis (FMEA), highlighting manual detergent dosing, unstable wash temperatures, lack of standard operating procedures (SOPs), and inconsistent employee performance as major contributors. During the Improve Phase, remedies that were specific to the problem were put into place. These included automating the delivery of detergent and controlling the temperature, adding real-time monitoring, updating standard operating procedures (SOPs), and giving employees more training. Because of this, the cleaning efficiency went up to 92%, the rework rate went down to 7.5%, and the inspection pass rate went up to 92%. Resource usage decreased significantly – detergent by 23% and water by 20% – resulting in annual cost savings of $23,404.24. These gains were sustained through the Control Phase via continuous monitoring, regular audits, and periodic staff retraining. The project shows that DMAIC may help improve operations and lower costs in a way that lasts. It gives other plants a model to follow if they want to improve their manufacturing processes while making them better for the environment and quality. Combining automation, data collection, analysis, and a standardized workflow within a framework for improvement led to rapid gains and long-term process control.

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1. Introduction

In bottle recycling operations, where stringent standards were required to satisfy regulatory and customer expectations, improving cleaning efficiency and reducing rework rates were essential for operational success. As recycling gained global importance, facilities faced growing pressure to accomplish more with fewer resources (AM, A. 2017). Maintaining consistent quality was particularly challenging in bottle recycling, given that food-grade cleanliness was frequently required. Bottles that failed to meet hygiene standards necessitated rework, which increased costs, wasted resources, and reduced overall productivity. This study employed the DMAIC (Define, Measure, Analyze, Improve, Control) methodology to streamline cleaning processes, minimize resource use, and enhance overall efficiency to address these challenges.

DMAIC was recognized as a structured, data-driven methodology for process improvement and quality management (Moreira et al., 2024). It leveraged statistical tools and process optimization techniques to identify the root causes of inefficiencies, thereby enabling sustainable solutions that enhanced productivity and environmental performance (Aichouni et al., 2021). As an integral component of Six Sigma, DMAIC effectively addresses complex operational challenges by systematically identifying and eliminating defects and inefficiencies (Garg et al., 2020). The framework offered a structured approach to problem-solving and continuous enhancement of processes, essential for achieving substantial quality improvements in business operations (Meena et al., 2018a).

The methodology has demonstrated effectiveness across diverse sectors, such as reducing garment manufacturing defect rates and improving engineering organizations' design processes (Rahman et al., 2018a). Its utility extended beyond manufacturing, as shown in applications that enhanced delivery efficiency and reduced deviation rates in production systems (Tennakoon & Palawatta, 2015a; Kaid et al., 2016). Moreover, the application of Six Sigma – particularly DMAIC – has consistently resulted in significant reductions in defect rates and substantial cost savings, including reported annual savings of US$2.4 million from reduced scrap and rework in manufacturing (Gijo et al., 2011). These outcomes underscored the universal applicability and transformative potential of DMAIC as a tool for operational excellence and financial viability across industries (Kumar & Sharma, 2012). This widespread success suggested that DMAIC could also revolutionize recycling practices by addressing recurring inefficiencies and operational constraints.

The emphasis of DMAIC on data-driven decision-making and continuous improvement make it particularly well-suited for recycling processes, which were often resource-intensive and characterized by high variability. Its systematic structure, beginning with the Define phase, facilitated the precise articulation of problems and guided data collection, which was vital for hypothesis development in complex systems (Cardiel-Ortega et al., 2017). The Measure phase quantified the magnitude of identified problems, established baseline metrics, and enabled accurate evaluation of improvement efforts. The Analyze phase then examined causal factors behind observed inefficiencies, using statistical tools to validate hypotheses and pinpoint root causes, providing a foundation for targeted interventions (Soundararajan & Reddy, 2020). The Improve phase focused on designing and implementing solutions to eliminate root causes, often involving innovative process redesigns or technological integration. Finally, the Control phase ensured that improvements were sustained over time by implementing monitoring systems and standardized procedures, which prevented regression and fostered long-term stability (Mittal et al., 2023).

This structured progression ensured that improvements were embedded into the operational framework, resulting in lasting gains rather than temporary fixes. The effectiveness of DMAIC in delivering sustainable results was evident in industrial applications such as the ceramic industry, where it improved process capacity and significantly reduced delayed orders (Maia et al., 2019a). Furthermore, DMAIC was recognized as a continuous improvement strategy that integrated Lean and Six Sigma principles, successfully advancing sustainability and environmental management across industrial sectors (Vargas & Scott, 2017a). Its five interconnected phases – Define, Measure, Analyze, Improve, and Control – systematically support organizations in problem-solving and process enhancement (Rahman et al., 2017). This robust and adaptable framework provided a proven pathway for identifying, analyzing, and mitigating inefficiencies, making it particularly effective for resource-intensive and complex processes such as those in recycling facilities (Prashar, 2020a).

Although DMAIC had been successfully applied in multiple industrial contexts – including the ceramic industry, where it reduced delayed orders and enhanced process capacity (Maia et al., 2019b) – its application in recycling operations, particularly in bottle cleaning facilities, remained limited. Recycling posed unique challenges due to variability in material quality, the need to meet stringent hygiene standards, and the dual objective of achieving economic efficiency while promoting environmental sustainability. This study addressed that gap by applying DMAIC to identify inefficiencies in cleaning operations, optimize resource utilization, establish robust inspection mechanisms, and integrate monitoring systems.

The primary aim of this study was to demonstrate that DMAIC could deliver tangible improvements in waste reduction, resource efficiency, and process reliability within bottle recycling facilities, thereby generating both environmental and economic benefits. The study covered the systematic identification of process inefficiencies and root cause analysis, and the implementation of targeted solutions to enhance cleaning efficiency, reduce rework, and optimize resource utilization. Specifically, in the Define phase, significant issues like improving detergent, setting inspection criteria, and keeping cleaning consistent are found. During the Measure phase, current performance metrics – like rework rates and resource consumption – are established as baselines. Root causes are then identified in the Analyze phase, utilizing tools like Fishbone Diagrams and Failure Mode and Effects Analysis (FMEA) to examine issues with detergent concentration, wash temperatures, and inspection procedures. The Improve phase tests out changes, such as setting standard wash temperatures and using the best detergent. On the other hand, the control phase adds real-time monitoring technologies and updated standard operating procedures (SOPs) to keep up with the advances already made.

The study has several limitations. First, it was limited to a single case study, so the findings may not be generalizable across other industries. Second, the study was based on operations data in a specific period and did not control external factors such as supplier quality differences or machine-planned maintenance schedules. Third, despite adopting the DMAIC technique as a structured guiding tool for data collection and analysis, it did not bring other continuous improvement frameworks, which could offer complementary perspectives. These limitations suggest that, while the results provide valuable insights into process improvement, further studies across multiple contexts, such as industry, organization, and methodological, are recommended to strengthen the findings.

What distinguished this study was its dual contribution: (1) improving operational efficiency by reducing rework rates and resource consumption, and (2) advancing sustainability goals by illustrating how structured quality improvement methodologies supported circular economy practices. This study advanced industrial practice and academic discourse by developing a replicable framework for applying DMAIC in bottle recycling facilities. The findings were expected to deliver immediate operational benefits and long-term contributions to sustainability, reinforcing the relevance of structured process improvement in fostering environmental stewardship and economic competitiveness.

2. Literature review

Six Sigma is a performance improvement approach that seeks to minimize errors and limit process variations, aiming to achieve a defect rate of 3.4 defects per million chances

(Chauhan & Belokar, 2015). At the heart of the analysis is the Define, Measure, Analyze, Improve, and Control (DMAIC) strategy, which is a structured and data-based path to identify non-value adding activities in the process, taking corrective actions, and sustaining the improved (Zhou et al., 2019). It has been accepted globally that Six Sigma has improved quality, reduced operational costs, and increased customer satisfaction in the automotive, electronics, and healthcare industries (Venkatesh et al., 2013; Bhargava & Gaur, 2021).

DMAIC is a systematic approach for improving processes that describes problem-solving as a progression from problem detection to sustainable control. Its incorporation of statistical process control techniques, Pareto charting, cause-and-effect diagrams, and other tools allows accurate analysis, evidence-based decision-making, and eliminates the need for educated guesswork (Bharath & Shankar, 2020; Megawati et al., 2020). Such a disciplined approach facilitates streamlined work processes and embeds process improvement and organizational learning (Mast & Lokkerbol, 2012).

DMAIC is the flexible toolset that has proven effective in all business areas. It has reduced healthcare errors and improved patient care (Rahman et al., 2018b). In garment making, it has improved the pace of production and has minimized variations (Monday, 2022). In the services domain, DMAIC is utilized to enhance customer satisfaction and process reliability (Tennakoon & Palawatta, 2015b). These myriad uses illuminate DMAIC's value in solving complex operational problems.

However, the DMAIC method has only had limited application in recycling operations – a critical area of sustainability. Contamination, feedstock variability, high product recycling rates, and peak and demand troughs have been identified as challenges to process efficiency and achieving environmental benefits in recycling facilities (Vargas & Scott, 2017b). Initial research also indicates DMAIC can overcome these problems by minimizing waste, enhancing material recovery, and enhancing throughput (Franchetti & Barnala, 2013; Meena et al, 2018b). For instance, the Define phase focuses on identifying inefficiencies, such as cleaning bottlenecks, and the Measure phase sets the current defect rates and energy or water usage (Gupta et al., 2021; Rajak et al., 2019). Subsequently, the Analyze phase exposes the causes of contamination, the Improve phase allows for focused redesign or upgradation of equipment, and the Control phase develops activities supporting operation in the long term (Cardiel-Ortega et al., 2017; Realyvásquez-Vargas et al., 2018).

Moreover, including sustainability measures in DMAIC extends the focus from quality to environmental responsibility. Embedding environmental performance indicators at each stage can enable organizations to reduce defects and environmental impact (Prashar, 2020b; Talapatra & Gaine, 2019). This two-prong strategy is a strategic recycling response to the process inefficiencies and white moral toppings of sustainability (Vargas & Scott, 2015c).

The uniqueness of this research is that DMAIC has been applied systematically to recycling activities, i.e., bottle cleaning, which are less researched in the literature. The research bridges operational excellence and sustainability by addressing shortcomings such as high rework rates and non-homogeneous cleaning quality. In addition, it broadens potential applications of DMAIC outside of traditional manufacturing sectors to a performance improvement protocol and a sustainable resource utilization strategy for recycling systems.

3. Experimental

A case study methodology was utilized in this research to assess the value of the DMAIC in improvements at the bottle-cleaning line in a recycling company. The study was an experimental in nature, having pre-measurements, a root cause analysis, interventions, and a post evaluation. DMAIC was chosen as it is a structured, data-driven approach, in which problems can be identified and optimization improvements can be sustained. DMAIC offers a transparent, replicable process roadmap that offers rigor and reproducibility much more than an ad hoc "problem-solving" approach. This makes it particularly suitable for recycling operations, where process variability and inefficiency are often overlooked yet critical to achieving environmental and economic goals.

The study was conducted in a mid-sized recycling facility specializing in bottle recovery and cleaning. The facility was affected by high rework rates caused by insufficient cleaning, leading to higher resource consumption of both materials and energy and higher labor costs. The experiments aimed to use DMAIC for: (a) identifying and measuring the defects in the cleaning process. (b) Analyze root causes of inefficiencies. (c) Take corrective actions to minimize the rework. (d) Install control systems in order to maintain the gains.

Application of DMAIC

Define Phase

The researcher first clarified the project scope and objectives through Stakeholder interviews, process observations, and initial data review, and isolated the key issues affecting the facility. The problem statement was: "The primary issues identified were a high rework rate necessitating multiple cleaning cycles for many bottles." With this result, the researcher set the research objectives: to achieve a rework rate of less than 10% and improve cleaning efficiency to 90%. A project charter was developed with specific roles, deliverables, and success metrics.

Measure Phase

Baseline performance data were collected over four weeks, covering rework rates, cleaning efficiency, inspection pass rates, detergent concentration, wash temperature, and daily water and detergent consumption. The results showed a 15% average rework rate, 84% cleaning efficiency, and an 84.5% inspection pass rate – well below targets. The variation of detergent concentration (3.8–5.0%), wash temperature (52–60°C), and lack of robustness made the cleaning inconsistent. Water and detergent consumption were 15,000 and 49.5 L/day respectively, indicating gross inefficiencies in the use of resources. These baseline measures were used as reference points for the effectiveness of follow-up interventions.

Analyze Phase

Two analysis techniques – Fishbone diagram and Failure Mode and Effects Analysis (FMEA) – were used to find and rank the causes of inefficiency. Human causes, such as a lack of master SOP training and high staff turnover, increased process variability as found in our study. At the same time, manual dosing, old heating control, and worn machines caused non-reproducible wash parameters. Physical inconsistencies, such as variable quality of the detergent used, impure water, and residual adhesive, also adversely affect cleaning efficiency. Failings of methods, such as a lack of written SOP and dependence on operator judgment in deciding cycle length, contributed to variability, as did environmental factors such as humidity and airborne contaminants, which delayed drying and contaminated the samples. The FMEA results ranked detergent variability (RPN = 400), insufficient SOP training (RPN = 378), lack of standardized cleaning processes (RPN = 378), and wash temperature fluctuations (RPN = 360) as the most critical issues, thereby providing evidence-based priorities for targeted improvement.

Improve Phase

Such interventions specifically targeted high-priority causes by technical, procedural, and organizational means. Technical improvements have been an automatic detergent dispenser (4.0% +/- 0.2%) and digital wash temperature control (55 degrees C +/- 2 degrees C), whereas real-time control methods have been an alarm and feedback for deviation. SOPs were developed for detergent dosing, temperature setting, cycle times, and adhesive control with associated training programs to maintain SOP use, focusing on high staff turnover positions. 5S audits and a preventative maintenance schedule were implemented to support discipline and equipment reliability. The implementation was phased over three months, beginning with preparation, piloting, and culminating in a full-scale rollout. Strong post-evaluation results were observed: 50% reduction in rework (from 15% to 7.5%), cleaning performance increased from 84% to 92%, inspection pass rate reached 92%, detergent and water reductions of 23% and 20%, respectively, were realized, and process control was achieved. A cost-benefit analysis further confirmed monthly savings of $1,950.35, with a payback period of less than five months for equipment and training investments.

Control Phase

To maintain these improvements, the digital sensors were equipped with alarm systems for the wash temperature and detergent concentration in a fixed installation. Standard operating procedures were revised and incorporated into training modules. Discipline and Compliance Worksheets. Incentives in the form of an incentive payment program. Incentives to adhere to protocol were reinforced during weekly audits and month-end performance reviews, the latter part of the period being designed to ensure disciplined use and compliance. Managers were updated regularly with live dashboards. Institutionalizing the changes ensured they were incorporated into the facility's daily processes and would be less likely to revert.

The detailed description of each DMAIC phase allows the replication of the experiment in similar recycling facilities. Other researchers or practitioners can try the method for their facilities on the condition of setting out the problem, creating the stabilization of the process, ordering and standardization of the actions, controlling the persistence of new criteria, creating better conditions for the implementation of guidelines, and developing and adjusting new goals. Replicability additionally benefits from the explicit description of the sampling strategy, data analysis types, and mitigation steps.

DMAIC was selected mainly due to its performance record in reducing process variation and defects in various industries, while providing flexibility to tailor for specific context applications, such as recycling. It consists of pre-specified phases per the study design, rendering the study flow from problem identification to sustainable solutions logical and based on evidence. In addition, the DMAIC approach allows for qualitative analysis to be supported by quantitative analysis, thus enabling the results to be verifiable and generalizable.

The novelty of this study lies in its systematic application of DMAIC to recycling operations, a field where continuous improvement tools are rarely applied rigorously. Whereas traditional recycling research is almost always material recovery- or technology-upgrade-centric, this study highlights that process discipline and operational excellence knowledge management technologies can be a key to improved recycling plant effectiveness – and thus to greener, better, cheaper recycling.

4. Results and discussion

The following section presents the outcomes of applying the DMAIC methodology to the bottle cleaning process, followed by a discussion of its implications. The results demonstrate how systematic interventions addressed process inefficiencies, while the discussion interprets these findings concerning operational performance and sustainability.

Define Phase

This phase incorporated stakeholder feedback (derived from interviews with facility and managers and staff, process observation, and initial data review) to isolate the root issue(s) and make focused interventions. The main issues identified were:

- High rework percentage – Bottles need to be cleaned multiple times in most cases to meet the required quality, and as a result, consume more resources and cause production delays.
- High water and detergent consumption – The variation in dosage and rinsing resulted in wastage and a higher cost of operation.
- Variability in cleaning performance – Inconsistent cleaning results were associated with a lack of control of critical parameters in the process, namely, detergent concentration and wash temperature.

The above results were, consequently, utilized to derive the following study objectives:

- Reduce the rework rate to below 10% within three months by addressing the root causes of cleaning inconsistencies.
- Reduce detergent usage by at least 20% through real-time monitoring and improved dosing practices.
- Enhance cleaning quality consistency by standardizing key parameters, such as detergent concentration and wash temperature.
- Increase cleaning efficiency to at least 90% by minimizing process variability.
- Improve inspection pass rates to at least 90% by enhancing cleaning quality and standardizing inspection protocols.

Measure Phase

Baseline measures were obtained over four weeks to benchmark the cleaning activity's status and measure any inefficiency. The performance indicators were inspection passes, cleaning efficiency, rework rate, detergent concentration, wash temperature, and daily water consumption. The measuring conditions were derived from early observations and stakeholder input collected in the Define Phase, and performance disparities and waste were indicated areas for the investigation. Table 1 shows the collected baseline data, revealing several critical findings that highlight inefficiencies.

Table 1. Baseline Data

Metric	Week				Average
	1	2	3	4	
Rework Rate (%)	14	17	15	16	15
Cleaning Efficiency (%)	84	85	82	83	84
Inspection Pass Rate (%)	85	84	86	83	84.5
Detergent Concentration (%)	4.2	3.8	4.5	5.0	4.4
Wash Temperature (ºC)	55	52	60	53	55
Water Usage (liters/day)	15,000	14,500	16,200	15,300	15,000
Detergent Usage (liters/day)	55	50	48	45	49.5

From the data collected, it was analyzed that the rework percentage was an average of 15%. Moreover, the presented weekly values ranged from 14% to 17%. This was higher than the target of no more than 10% of bottles to be subject to rework, which means that many bottles were not meeting cleaning criteria on the first run and required an additional cleaning process. Average cleaning efficiency was 84% and showed low variability (82–85%) over the week. The degree of efficiency in this process indicated that while acceptable quality was achieved for a proportion of the product, a considerable amount of output did not meet standards during the first production stage. This was also confirmed by an average pass rate of 84.5%. The strong correlation between cleaning efficacy and inspection pass rate indicated that inspection failures were mainly a result of cleaning process inconsistency.

When the researcher examined operating parameters more closely, he found significant variations that were causing these gaps in efficiency. The detergent concentration varied from 3.8 to 5.0%, with a mean of 4.4%. This variability was mainly due to manual dosing practices, so accurate chemical application control was not possible. Likewise, wash temperatures ranged from 52°C to 60°C, with a 55°C average, below recommendations that made the detergent less effective. When the temperature did not fall in the desired range, detergent enzymes could not activate (Dahili et al., 2015). These unstable conditions resulted in inconsistent cleaning and affected rework and inspection rates. Resource utilization figures even revealed further degradation in operational efficiency. The average daily water use was 15,000 liters, ranging from 14,500 and 16,200 liters, and the average consumption of detergents was 49.5 L per day, ranging from 45 and 55 L. These changes indicated a loss of process control and that excessive resources were consumed to mitigate quality problems due to an earlier process instability.

Analyze Phase

The Analyze Phase sought to uncover the underlying causes of the inefficiencies observed in the cleaning process, as revealed in the Measure Phase. There was clear evidence of inconsistent cleaning performances when the baseline data were reviewed: a rework rate of 15%, a cleaning efficiency of 84% and an inspection pass rate of 84.5%. Two key analytical aids were used to investigate these problems more thoroughly: the Fishbone Diagram (Figure 1) and the Failure Mode and Effects Analysis (FMEA) (Tables 2 and 4). Using these tools, the researcher could classify, visualize, and rank the contributors to process variability and inefficiency.

The Fishbone Diagram is a valuable tool for finding the core cause of a problem. It divides these components into five main groups: Man, Machine, Material, Method, and Environment, providing a structured approach to understanding the multifaceted nature of process inconsistencies. In the category of "man," several contributing factors dictate how clean something will be. One of these is inadequate training on standard operating procedures. When there is insufficient training, staff often rely on their own opinion, which causes them to diverge from the set protocols and leads to an indiscriminate manner of operating cleaning cycles and using detergents. The high staff turnover exacerbates this problem because new staff members may not have received formal training. As a result, this may maintain the discrepancies in cleaning modes that ultimately may lead to the loss of the efficiency of the cleaning process (Boyce, J., 2016a). Another contributing factor is that the skill level among the workers is diverse; some of them may lack experience or expertise and therefore may not be able to carry out the cleaning task to the required standard consistently. The lack of documented and easily accessible SOPs worsens these problems by leaving operators without a dependable reference point and encouraging subjective perceptions (Schahawi et al., 2021).

Analysis of machine aspects has highlighted several significant mechanical drawbacks that compromised the consistency as well as the performance of the cleaning process. Manual adding of detergent, a simple step in appearance, brought up many differences in the detergent concentration and led to poor cleaning and higher usage. This inconsistency directly compromised the cleaning quality, as the concentration of detergents varied based on human error and the lack of precise measurement tools, leading to either under-cleaning due to insufficient detergent or over-cleaning and excessive waste due to excess detergent (Stefánsdóttir et al., 2017a). In addition, obsolete heating controllers were identified as a significant cause of temperature variation over wash cycles, again affecting correct detergent solubilization and general wash performance. It is crucial to correctly manage the temperature so that the detergent chemicals can work. Any temperature changes could make cleaning less effective, especially in places where strict hygiene requirements are needed (Boyce, J., 2016b). Wear and tear on the equipment, especially blocked nozzles, worsened the situation by making the detergent unevenly spread across the cleansed surfaces. These obstructions disturb the smooth spray pattern and cause some areas to be insufficiently covered with detergents, while others receive too much. The mechanical difficulties caused the whole cleaning process to lose harmony, making people wonder how trustworthy and repeatable the cleaning was. Keeping the temperature and mechanical consistency in high-throughput operations is very important for chemical cleaning to work well.

Regarding ingredients, the leading causes were differences in detergent quality from different suppliers and dirty water. The quality of detergent may vary. For example, the concentration of active substances can be different, there can be undesired byproducts, and the physical qualities of the detergent components can be various. These kinds of differences can make the detergent less effective at cleaning and make it work in strange ways. The examination also concluded that the water supply was not clean. Dissolved organic matter and microbiological contamination are two examples of these impurities. They can interact with detergent components and start chemical processes that the detergent does not want to happen, making it less effective and affecting its long-term stability (Aadil et al., 2019). Thus, water quality is a critical control point that requires careful monitoring and treatment to ensure consistent detergent quality.

Residual adhesives remaining on the bottles presented another source of material-related complications. These adhesives, often used for labeling or tamper-evident seals, can be difficult to remove completely during the bottle washing, especially if the adhesives have aged or been exposed to adverse environmental conditions. The presence of residual adhesive can interfere with the proper adhesion of new labels, compromising the integrity of the bottles (Garcia-Garcia et al., 2021). Finally, there were different degrees of bottle residue to account for. This residue, which includes dust, dirt, or other particulate material, can arise from some causes, such as bottle making, storage, and shipping.

The absence of standardized operational procedures, particularly within the Method category, impedes achieving consistent and efficient outcomes (Stefánsdóttir et al., 2017b). There is too much variation in the cleaning process since there are no defined standard operating procedures for the washing process, such as how to dose detergent and control temperature, and how to handle bottles. Because of this lack, operators must rely on their opinions to decide how long to run the cleaning cycle instead of using objective criteria. Such discretionary practices inevitably result in inefficient resource utilization, manifesting as inconsistencies in cleaning efficacy, unwarranted consumption of detergents, energy wastage through non-optimized temperature settings, and extended cycle times (Hung et al., 2022). These procedural deficiencies have significant implications from a work systems perspective and the cleaning process's overall quality and reliability, which could impair downstream processes and product quality and safety (Boyce, J., 2016c).

The performance and efficacy of the bottle washing process were significantly affected by the surrounding environment, and overall drying kinetics were principally governed by the exposure of the empty container to the relative humidity. In places with high relative humidity and poor ventilation, the evaporation stage took a lot longer, making processing each batch of bottles take longer. This slowdown in throughput made the cleaning mechanism less effective and made the sanitized bottles more likely to get dirty again from airborne bacteria and particles (Boyce, J., 2016d). The introduction of dust and other airborne particles into the cleaning environment, a consequence of inadequate filtration systems, further compromised the integrity of the cleaning process. This particulate matter, which commonly contains microbiological impurities, is deposited on the bottles after cleaning and forms visible deposits that require further processing or cause failure of cleaned bottles during quality control checks. Such particles not only spoil the aesthetics of bottles but could also be a health hazard, especially in the case of food and drink containers (Betoret et al.,2016).

Long drying times can have effects beyond just making things less efficient; they could even defeat the aim of the cleaning procedure, which is to get rid of dirt and germs (Mousavi et al.,2019). Drying slows down the growth of microbes or harmful chemical processes (Battaiotto et al.,2020). The drying step should be strictly controlled, as too fast evaporation may trigger the generation of undesired amorphous particles (Shakiba et al., 2019). Moist residues on bottles favor the development of residual microorganisms and result in the uselessness of the initial cleaning and sanitization step (Donno et al., 2025). Moreover, moisture can contaminate the surrounding air when the air is bad, affecting relationships between humidity, ventilation, and filtration. Once again, these data prove that controlling the environment in a bottle cleaning facility is holistic.

To prioritize these issues for targeted improvement, the researcher conducted a Failure Mode and Effects Analysis (FMEA) as presented in Table 2. It involved several key components that helped analyze risk and prioritize corrective actions. The category defines the specific component. Within this category, the Function outlined the intended operation, answering the question of what the process was supposed to do. Specific Requirements were established to ensure performance. A Failure Mode describes how a part or process could fail when these requirements are not fulfilled. Each Failure mode had an associated Failure Effect, which described what would happen in the event of a failure in the system or for the end user, including performance, safety, or customer satisfaction. Finally, the list of failure causes shows what might have gone wrong. This thorough study allowed the researcher to determine how risky something was, what steps should be taken first depending on how serious, likely, and detectable it was, and how to improve things to improve reliability and quality.

Each failure mode was assessed in a structured brainstorming session with the supervisors, operators, and the owner. The Researcher facilitated consensus on the Severity (S), Occurrence (O), and Detection (D) values by combining stakeholder experience, historical data, and process knowledge. The group assigned quantitative ratings to S, O, and D using a standardized 1–10 scale as presented in Table 3. Severity scores reflected the potential seriousness of the effect on performance, safety, or customer satisfaction. Occurrence scores represented the estimated likelihood of the failure cause happening. The detection scores represented the likelihood of finding the failure before reaching the end-user. Moreover, the Risk Priority Number (RPN) was obtained by multiplying the three values (S × O × D). Table 4 summarizes the RPN values.

Table 3. Rating Scale for Severity (S), Occurrence (O), and Detection (D)

Rating	Severity (S) Effect of Failure	Occurrence (O) Likelihood of Failure	Detection (D) Likelihood of Detection
1	No effect	Failure almost impossible	Almost certain detection
2	Very minor effect; negligible impact	Remote failure	Very high likelihood of detection
3	Minor effect; slight inconvenience	Extremely rare failure	High likelihood of detection
4	Noticeable effect; some dissatisfaction	Very rare failure	Moderate to high likelihood of detection
5	Moderate effect; rework required, some efficiency loss	Rare failure; occurs less than once a year	Moderate likelihood of detection
6	Significant effect; partial function loss, reduced performance	Infrequent failure; occurs yearly	Low to moderate likelihood of detection
7	Major effect; strong dissatisfaction or safety concern	Occasional failure; occurs several times a year	Low likelihood of detection
8	Severe effect; system disruption or high dissatisfaction	Likely failure; occurs monthly	Very low likelihood of detection
9	Critical effect; major safety issue or near-total system loss	Frequent failure; occurs weekly or often	Extremely difficult to detect
10	Catastrophic effect; hazardous failure or complete system shutdown	Very frequent failure; occurs almost every cycle	Almost impossible to detect before reaching end user

A change in detergent concentration during the dispensing phase was the most prominent failure mechanism, with an RPN of 400. This illustrates that irregular amounts of chemicals might make the cleaning procedure far less effective and reliable (Lo et al., 2018). There are several reasons why this can happen, such as broken dispensing equipment, poor calibration methods, or differences in the detergent formulation itself. These can result in suboptimal cleaning results (Bubenik et al., 2025). Lack of training on SOPs and non-existence of standard cleaning protocols were reported as high-priority concerns, with both getting an RPN of 378, highlighting the importance of human factor principles and procedural clarity in maintaining process performance and effectiveness (Jain, K., 2017). Insufficient training could, in turn, cause deviation from set procedures and then influence the cleaning steps' reproducibility and the process's overall quality (Andrada et al., 2018).

Wash temperature (RPN=360) variation and inadequate inspection instrument (RPN=288) also emphasize the importance of equipment calibration and robust quality assurance measures in maintaining effective cleaning operations. Changes in the wash temperature may affect the detergents' cleaning and/or disinfecting effectiveness, resulting in incomplete cleaning and/or damaging the cleaned material. Poor or out-of-calibration inspection equipment can contribute to failing to ensure cleanliness meets criteria while allowing items that have been inadequately cleaned to move forward, increasing the potential for cross-contamination. Equipment deterioration with an RPN of 270 and residual variation, RPN 196, indicated that proactive maintenance programs and improved cleaning agent selection would be necessary to prevent potential process interruptions. An RPN of 192 suggests that variable cleaning cycle duration, due to high employee turnover and undefined cleaning conditions, is difficult to control within process parameters that are not workforce dependent. Environmental factors, including high humidity and poor ventilation, were rated at an RPN 168. As for the dust and contaminants present in the plant, these received an RPN of 140, suggesting significant process loss potential, so complete environmental control is required. Categorizing different arrangements and cleaning methods is necessary to optimize resource management (Stefánsdóttir et al., 2017c).

To summarize, the Analyze Phase determined that the cleaning process inefficiencies resulted from process variability in the form of: Human error, Outdated equipment, Inconsistent materials, and a lack of standard work. Combining Fishbone and FMEA tools made it possible to visualize mainly quantitative analysis of root causes. Supported by relevant research, the results showed that the next phase – Improve – must focus on automating critical variables (especially detergent dosing), stabilizing wash temperature, introducing SOPs, enhancing operator training, and upgrading equipment reliability. These targeted actions are expected to reduce rework, improve cleaning efficiency, and meet the quality targets set at the beginning of the DMAIC cycle.

Improve Phase

The Improve Phase focused on implementing targeted solutions to the high-priority root causes identified in the Analyze Phase. Drawing from the results of the FMEA, baseline performance data, and stakeholder feedback, the primary goals were to enhance cleaning consistency, reduce resource wastage, and improve overall operational efficiency.

To address inconsistent wash temperatures – identified as a critical root cause – digital temperature controllers were installed. These devices maintained the wash temperature within the optimal range of 55°C ± 2°C. Integrated alarms alerted operators to deviations, and SOPs mandated 15-minute interval checks, weekly calibration, and immediate corrective action in the event of deviations. This practice helped maintain the temperature, which, as already mentioned, was necessary for successful detergent activation and uniform cleaning results. At the same time, the labor-intensive application of detergent, which introduced additional inconsistency, was replaced with an automated dispensing system set to administer detergent at a constant concentration of 4.0% ± 0.2%. Flow sensors monitored dosage, and any deviation beyond 0.5% triggered system pauses and recalibration. Operators conducted calibration checks at the start of each shift, used certified detergents, and logged detergent use per shift. These process controls reduced chemical waste and standardized cleaning quality.

Real-time monitoring of wash temperature and detergent concentration was provided through sensors. This allowed the sensors to transmit data to the supervisors, making it possible to take corrective action in real time to increase traceability. Weekly reports were discussed at process audits for performance trend monitoring. Performance trends were monitored during process audits by reviewing the weekly reports. In support of these technical upgrades, updated standard operating procedures were developed to define precise actions for detergent dosing, temperature setting, handling of bottles with adhesive residues, and adherence to a maximum cycle time of seven minutes. To address workforce variability, employees received comprehensive training on the new systems, and high-turnover positions were given focused attention to ensure consistency. Weekly 5S audits were conducted using standardized checklists, and equipment calibration, adherence to SOPs, and cleaning output quality were evaluated.

These results have substantial environmental benefits. Lower detergent consumption decreases the chemical load in wastewater, minimizing the potential for aquatic toxicity and reducing the environmental footprint of effluent discharge. Reduced water usage conserves a critical natural resource and decreases the volume of wastewater that must be treated before release, thereby reducing energy and chemical demands for wastewater treatment.

The implementation was carried out over three months in preparation, piloting, and evaluation, and the first month involved installing the new systems and finalizing SOPs. Intensive training was conducted to correct non-adherence identified in the baseline phase during this time, and in the second month-initiated piloting of the systems in controlled batches. Real-time data on wash parameters and cleaning quality were collected to assess the effectiveness of the interventions. The final month saw full-scale implementation and evaluation, which confirmed significant improvements across all performance metrics. Table 5 compares the KPI's before and after implementation, focusing on reduced inspection pass rate, resource efficiency, and general cleaning consistency.

Table 5. Comparative Analysis of Baseline and Post-Implementation Data

Metric	Baseline (Pre-Implementation)	Post-Implementation	Improvement
Rework Rate	15%	7.5%	50% reduction
Cleaning Efficiency	84%	92%	8% improvement
Inspection Pass Rate	84.5%	92%	5.5.% improvement
Detergent Concentration	4.4% (manual dosing variability)	4.0% ± 0.2% (automated)	Standardized
Wash Temperature	52°C – 60°C	55°C ± 2°C	Standardized
Water Usage (liters/day)	15,000 liters	12,000 liters	20% reduction
Detergent Usage (liters/day)	49.5 liters	38 liters	23% reduction

A cost-benefit analysis confirmed the economic viability of the project. Monthly savings reached $1,950.35, driven by reduced water use ($392.69), detergent savings ($903.18), and lower rework-related costs ($654.48). With an investment of $8,726.41 in equipment upgrades, training, and process standardization, the payback period was under five months. These results show that the initiative made things more efficient, ensured the economy would stay strong, and set the facility up for better long-term performance. Table 6 shows a side-by-side comparison of the cost indicators to clarify things.

Table 6. Comparative Analysis of Costs

Metric	Baseline Costs	Post-Implementation Costs	Savings
Water Usage ($/month)	$1,963.44	$1,570.75	$392.69
Detergent Usage ($/month)	$3,887.62	$2,984.43	$903.18
Rework Costs ($/month)	$1,308.96	$654.48	$654.48
Total Costs ($/month)	$7,160.02	$5,209.67	$1950.35

Control Phase

The Control Phase aimed to sustain the improvements achieved during the improvement phase and ensure continued operational efficiency (Garza-Reyes et al., 2016). This step was about how to take what had been done and make it part of the culture via monitoring, revised SOPs, continual management audits, and further and ongoing staff training. The facility installed a real-time monitoring system integrated with digital sensors to maintain the optimized wash temperature and detergent concentration. These sensors gave feedback on temperature (55°C ± 2°C) and detergent (4% target), and alarm systems were built to alert the operators to deviations and prompt corrective actions to be taken promptly. This provided automated data collection that allowed for trending and accountability.

New standard operating procedures (SOPs) were developed and disseminated to the employees to ensure consistency in cleaning processes. Detergent dispensing using the automated system, setting and monitoring wash temperatures, and the frequency of equipment maintenance are included in the guidelines. The method of inspecting bottles post-cleaning and reducing human error by implementing automated visual inspection systems, where applicable, is also included in the SOPs. Periodic training sessions were conducted for all staff, focusing on using the new monitoring systems and adhering to updated SOPs. The training focused on skill gaps identified in the fishbone analysis and the necessity of following processes with careful devotion. An intensive training program was also developed to support standard operating procedures on how the correct setup and fault troubleshooting should be carried out to guarantee long-term performance. Finally, an audit process and performance review were implemented to audit for SOP compliance and system performance. The audit was carried out weekly to assess the significant variables such as rework percentages, quality of cleaning, and consumption of resources, which were audited and summarized into head-wise monthly reports to keep the management informed about the progress and anticipate future problems. Collectively, these changes contribute to a more sustainable cleaning process, demonstrating that DMAIC interventions can simultaneously achieve operational efficiency and environmental stewardship.

5. Summary and conclusion

The DMAIC approach was crucial in helping to resolve the operational issues within a facility's cleaning process, yielding quality, proper resource usage, and cost-effectiveness. Establish clear goals for the project -specifically rework reduction, increased cleaning consistency, optimized resource usage, and standardized process parameters – during the Define Phase. The Measure Phase provided baseline data showing a high % rework rate of 15%, suboptimal cleaning efficiency of 84%, and excessive detergent and water consumption. The Analyze Phase helped to identify root causes of these inefficiencies – manual detergent dosing, unstable wash temperatures, a lack of standard procedures, and a lack of operator training.

Based on these findings, the Improve Phase implemented targeted solutions: automating detergent dosing, stabilizing wash temperatures through digital controls, deploying real-time monitoring with sensors, updating standard operating procedures, and conducting structured training programs. These actions led to significant performance improvements – reducing the rework rate to 7.5%, increasing cleaning efficiency to 92%, and improving the inspection pass rate to 92%. Detergent concentration and wash temperature were consistently maintained at 4.0% ± 0.2% and 55°C ± 2°C, respectively, while detergent and water usage were reduced by 23% and 20%, aligning with environmental sustainability goals. The Control Phase embedded these improvements into routine operations through real-time dashboards, SOPs, weekly audits, and periodic staff retraining. Economically, these changes translated into an annualized savings of $23,404.24, with a return on investment achieved in less than five months.

To ensure long-term success, it is recommended that the DMAIC model be replicated in other processes within the facility, supported by the institutionalization of DMAIC training, integration of advanced analytics for predictive monitoring, regular reviews of SOPs and performance indicators, and alignment of quality goals with broader sustainability initiatives. Thus, all Define Phase targets were fully realized, confirming the effectiveness of DMAIC in achieving both operational and sustainability objectives.

The results of this study indicated that applying the DMAIC method will lead to a substantial increase in the reliability of processes, cost-efficiency use of resources, and reduction in wastage during bottle recycling. By analyzing existing cleaning protocols, identifying bottlenecks, and implementing targeted interventions, measurable gains were achieved in cleaning consistency, detergent use, and rework reduction. These results align with findings reported in the wider Six Sigma literature – particularly regarding the methodology's capacity to reduce variation and enhance process capability. This study offers a novel contribution by demonstrating its adaptability and effectiveness in the underexplored context of recycling operations. It provides Filipino and global entities a methodology for systematically addressing productivity, efficiency, and long-term process capabilities. The claimed benefits were like those reported in more established industries such as automotive and electronics, confirming that DMAIC is applicable across various industries. However, it remains to be further investigated whether the magnitude of improvements achieved here surpasses or merely parallels those in similar industries. As a result, future studies need to compare performance across different contexts and industries to extend existing knowledge on the applicability of DMAIC as a holistic tool for improving operational performance and environmental sustainability.

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Appendix

Appendix A
Table 2. Failure Mode and Effect Analysis

Category	Function	Requirements	Failure Mode	Failure Effect	Failure Causes
Man	SOP Adherence	Consistent process adherence	Insufficient training on SOPs	Non-adherence to cleaning processes, leading to errors	Lack of initial training, infrequent refresher programs
			High employee turnover	Knowledge gaps, process inconsistency	Frequent staff changes, insufficient onboarding
Machine	Detergent Dispensing	Accurate detergent dispensing	Variability in detergent concentration	Inconsistent cleaning results	Manual detergent dispensing
			Equipment wear and tear	Uneven detergent application, cleaning inconsistency	Lack of regular replacement
	Heating Controls	Maintain a stable washing temperature	Wash temperature fluctuations	Reduced cleaning efficiency, inconsistent results	Outdated equipment, insufficient calibration
	Inspection Tools	Accurate detection of cleaning defects	Inadequate inspection tools	Missed cleaning defects, reduced inspection quality	Manual inspection methods
Material	Detergent Quality	Consistent and effective detergent quality	Variability in detergent quality	Decreased cleaning efficiency, rework requirements	Inconsistent suppliers, standard detergent quality
	Water Quality	Effective Detergent performance	Impurities in water	Reduced detergent effectiveness, poor cleaning	Untreated water
	Bottle Residue Removal	Efficient removal of all residues	Residue variability	Increased cleaning times, rework due to residue	Variation in the incoming bottle quality
Method	Cleaning Process	Standardized cleaning steps	Lack of standardized cleaning	Variability in cleaning outcomes	Absence of formalized SOPs for key parameters
	Cleaning cycle	Optimized resource use during cycles	Inconsistent cleaning cycle lengths	Waste of resources, inconsistent cleaning quality	Operator discretion in cycle duration
Environment	Facility Cleanliness	Clean facility environment for optimal results	Dust and debris in the facility	Increased rework and contamination	Poor cleaning protocols, facility maintenance issues
	Humidity and Ventilation	Controlled environment for drying	High humidity and Inadequate ventilation	Increased drying time, reduced throughput	Poor ventilation

Table 4. Risk Priority Number (RPN)

Category	Function	Failure Mode	S	O	D	Risk Priority Number (RPN)	Rank
Man	SOP Adherence	Insufficient training on SOPs	9	7	6	378	2
		High employee turnover	8	6	4	192	7
Machine	Detergent Dispensing	Variability in detergent concentration	10	8	5	400	1
		Equipment wear and tear	9	6	5	270	5
	Heating Controls	Wash temperature fluctuations	9	8	5	360	3
	Inspection Tools	Inadequate inspection tools	8	6	6	288	4
Material	Detergent Quality	Variability in detergent quality	8	5	4	160	9
	Water Quality	Impurities in water	8	5	4	160	9
	Bottle Residue Removal	Residue variability	7	7	4	196	6
Method	Cleaning Process	Lack of standardized cleaning	9	7	5	378	2
	Cleaning cycle	Inconsistent cleaning cycle lengths	8	6	4	192	7
Environment	Facility Cleanliness	Dust and debris in the facility	7	5	4	140	10
	Humidity and Ventilation	High humidity and Inadequate ventilation	7	6	4	168	8

Appendix B

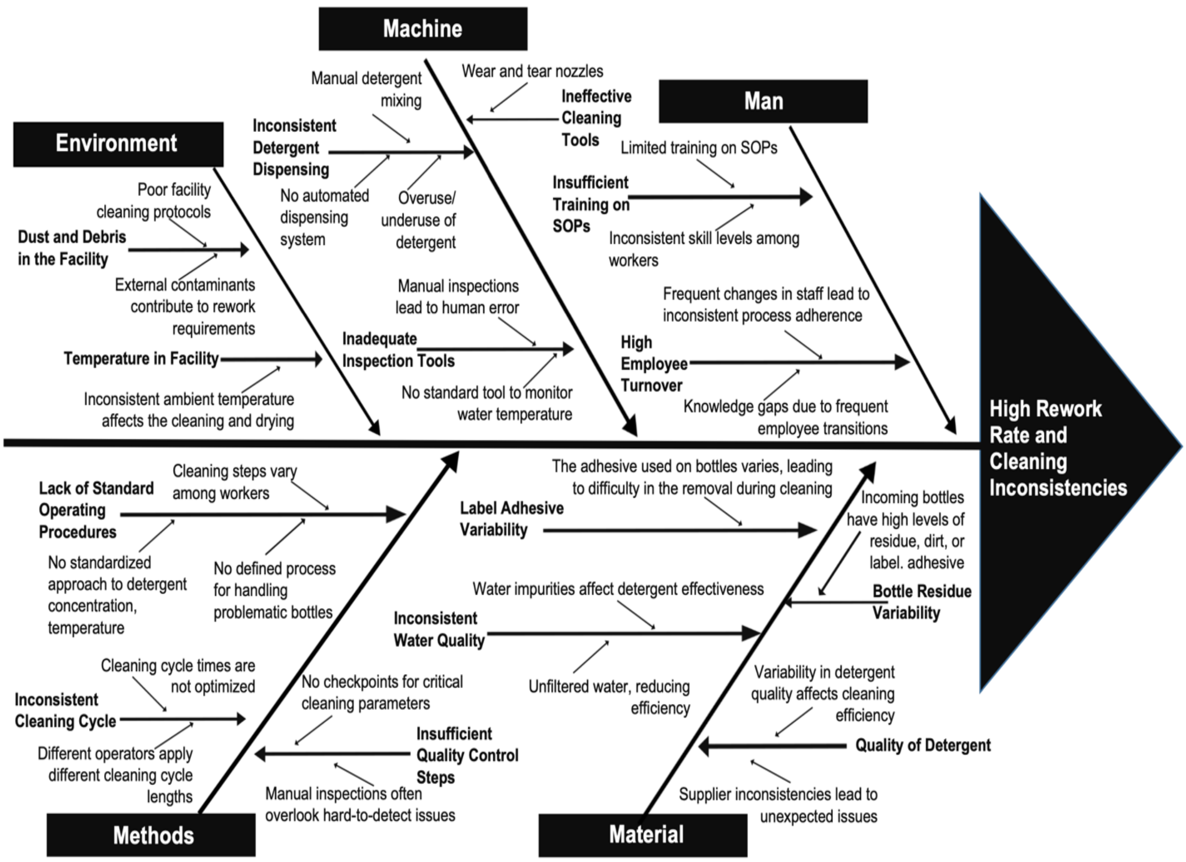

Fig. 1. Fishbone Diagram