

Improving Surface Finish Quality of Plastic Molds via VSM and DMAIC Integration

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Abstract

The rapid growth of manufacturing demands continuous process improvement. This study examines a plastic manufacturing company's Mouldshop, which has not met performance targets an average lead time of 52 days (target 50 days) and a 75% success rate (target 93%) and struggles to achieve the desired surface finish quality of plastic molds. An integrated Value Stream Mapping (VSM) and Six Sigma DMAIC approach is applied to visualize end-to-end process flows (VA/NNVA/NVA), quantify performance gaps, analyze root causes (Fishbone with the 4M Man, Machine, Material, Method), and design improvements. VSM reveals three dominant wastes defects, inappropriate processing, and waiting linked to six critical failure causes spanning operator capability and discipline; overloaded schedules, equipment failures, machining errors, temperature control, and precision instability; material selection and procurement delays; and shortcomings in work- instruction compliance, machining parameters, drawing completeness, and standardized process flow. Using 5W+1H within DMAIC, the study proposes: standardized machining instructions and setup times; preventive- maintenance schedules and checklists; incoming verification with PIC accountability; structured training; mold quality checklists; weekly 5S/5R audits; and Future State Mapping to reduce NNVA/NVA. The integrated DMAIC-VSM roadmap is expected to shorten lead time, raise the value-added ratio, and improve surface finish quality, offering a transferable blueprint for similar manufacturing operations.

Keywords: value stream mapping (vsm), six sigma, dmaic, mold making process, surface finish quality.

INTRODUCTION

The rapid advancement of the global manufacturing industry has intensified competition, compelling companies to optimize production processes to enhance efficiency and product quality (Ahmed et al., 2019). In the plastic manufacturing sector, achieving a high-quality surface finish in molds is crucial, as it directly affects product performance and customer satisfaction (Seham et al., 2023; Desai & Prajapati, 2017). However, many companies face inefficiencies in mold development, which result in longer production times, increased costs, and higher defect rates (Jirasukprasert et al., 2014; Merjani et al., 2023).

The company analyzed in this study, a plastic manufacturing firm, is currently struggling to meet production targets in its Mouldshop division. In particular, it fails to consistently achieve the desired surface finish quality of plastic molds. The mold development process currently requires an average of 52 days exceeding the target of 50 days while the success rate lags at just 75%, falling far short of the 93% benchmark. These performance gaps not only hinder the company's ability to meet customer expectations but also lead to increased operational costs and lost competitiveness, underscoring the urgent need for systematic process improvement. These inefficiencies can be attributed to prolonged machining processes, inadequate mold mechanisms, non-conforming trial product flexibility, delays in polishing, and limited machine availability for testing (Zulkarnaen & Widodo, 2023; Krist, 2017).

To address these challenges, this study applies the Value Stream Mapping (VSM) tool alongside the Six Sigma DMAIC (Define, Measure, Analyze, Improve, and Control) methodology. VSM is widely used in lean manufacturing to map production workflows, identify value-added (VA), non-value-added (NVA), and necessary but non-value-added (NNVA) activities, and detect areas of inefficiency (Lean Enterprise Institute, 2023). DMAIC, on the other hand, provides a structured framework for identifying process inefficiencies, removing waste, and implementing quality improvement strategies (Six Sigma Online, 2023; Investopedia, 2010). Several empirical studies have validated the effectiveness of combining VSM and DMAIC in reducing defect rates, optimizing setup times, and improving production outcomes in various manufacturing sectors (Seham et al., 2023; Desai & Prajapati, 2017; Jirasukprasert et al., 2014; Merjani et al., 2023; Zulkarnaen & Widodo, 2023; Krist, 2017).

While numerous studies have applied Six Sigma and Value Stream Mapping independently to improve manufacturing processes (Ahmed et al., 2019; Seham et al., 2023; Desai & Prajapati, 2017; Jirasukprasert et al., 2014; Merjani et al., 2023), limited research has addressed their combined application specifically within the context of plastic mold surface finish enhancement. Most prior works focus on general defect reduction or cycle time improvement in broader manufacturing environments (Seham et al., 2023; Desai & Prajapati, 2017). Furthermore, few studies incorporate quantitative performance benchmarks such as success rates and lead times as critical indicators for process improvement in mold development. This study contributes a novel approach by integrating VSM and the DMAIC framework to tackle specific quality challenges in the mouldshop division of a plastic manufacturer, aiming not only to reduce defects but also to directly improve surface finish quality, a key metric often overlooked in earlier research. The contextual application to a real-world case with measurable targets further distinguishes this research from prior academic and industrial studies.

By integrating VSM and DMAIC, this research aims to identify the root causes of inefficiencies in the mold development process and propose practical solutions to enhance surface finish quality, reduce lead times, and boost overall productivity. The results of this study are expected to contribute valuable insights into process optimization strategies applicable to other plastic manufacturing environments.

METHOD

This study employs an integrated methodology based on Value Stream Mapping (VSM) and the Six Sigma DMAIC (Define, Measure, Analyze, Improve, Control) framework to address inefficiencies in plastic mold manufacturing. The methodology is divided into five clearly defined stages, each with specific outputs and measurable achievement indicators, and

builds on previous research accomplishments in lean manufacturing and process optimization.

In the initial phase, a comprehensive assessment of the existing mold-making process is conducted. Using VSM, the research team documents all process steps, distinguishing between value-added, non-value-added, and necessary but non-value-added activities. Data collection methods include process observations, interviews with key personnel, and reviews of existing performance records. The main outputs from this stage include a detailed process map of the mold-making operation, baseline performance metrics for cycle time, defect rate, and surface finish quality, as well as the identification of at least three major bottlenecks. Measurable indicators include the completion and validation of the process map with stakeholder approval and documented baseline KPIs (e.g., current cycle time of 52 days and a 75% success rate).

Building on the baseline analysis, both quantitative and qualitative data are gathered to test hypotheses regarding production inefficiencies. Methods employed include time studies, quality audits, and surveys among operators and engineers. Statistical sampling and preliminary analyses are then applied to identify potential correlations between process variables and performance outcomes. The outputs of this stage include a robust dataset capturing key process parameters and formulated hypotheses on critical inefficiencies, such as the impact of trial product flexibility on overall success rate. The measurable indicators are a minimum sample size sufficient to achieve statistical significance and at least two validated hypotheses with p-values below a predetermined threshold (e.g., $p < 0.05$).

In this phase, statistical tools such as ANOVA, regression analysis, and Design of Experiments (DOE) are used to uncover the root causes of identified inefficiencies. The analysis quantifies the effect of each variable on production performance and prioritizes improvement actions. Outputs include a comprehensive root cause analysis report and a prioritized list of improvement opportunities with quantified potential benefits. The measurable indicators are the identification of all critical root causes contributing to process delays and defects, and the estimation of potential improvements expressed in percentage gains (e.g., reducing cycle time by at least 10% or increasing the success rate towards the 93% target).

Based on the analysis, targeted interventions are designed and implemented. This phase involves piloting improvements in key areas such as machining process optimization, enhanced mold mechanisms, and improved trial protocols. Controlled experiments and simulation models are also employed to refine these interventions before full-scale implementation. The outputs include documented improvement plans, pilot study results, revised process protocols, and training modules for staff. Measurable indicators are a reduction in cycle time (e.g., achieving or surpassing the target of 50 days), an increased success rate measured through pilot studies (targeting the move from 75% to 93%), and quantifiable reductions in defects as measured by quality audits.

In the final stage, the implemented changes are validated and standardized through continuous monitoring and control mechanisms. Real-time data acquisition systems, such as IoT-enabled sensors and dashboards, are established to track ongoing performance. The Control phase of DMAIC ensures that improvements are sustained and any deviations promptly addressed. Outputs include a validated, optimized mold-making process with embedded control systems, as well as continuous improvement plans and periodic performance review reports. Measurable indicators are the achievement of target KPIs maintained over a defined monitoring period (e.g., 93% success rate, 50-day cycle time).

maintained for six consecutive months) and regular performance reports indicating sustained process stability and improvement trends.

RESULT AND DISCUSSION

New Mold Production Achievement Analysis

The achievement analysis indicates that the lowest performance occurred in July and December, with a completion rate of only 50%, or three molds produced within each month. This low achievement was primarily due to discrepancies found during the mold trial process, including machining process delays (CNC, milling, grinding, turning, polishing, assembling, and trial) which occurred 10 times; locking mechanism mismatches with the sample 8 times; product flexibility issues 3 times; unavailability of trial machines 3 times; mechanical failures of the mold during trial 1 time; and delayed polishing processes 1 time.

In May, the production rate was 0% due to a mutual decision between management and operations. All requests for new mold production from marketing were suspended because of the extended Eid holidays, and the Mouldshop department was instructed to focus on repairing molds already in use.

Define Phase Analysis

1. SIPOC Diagram Analysis

The SIPOC diagram outlines the mold production flow as follows:

- Suppliers: Mouldshop department as the internal supplier for the production department.
- Inputs: Materials, steel components, heaters, cooling components (nipple), cutting tools, labeling, drawings, and CNC cutting programs.
- Processes: Machining (CNC, milling, turning, grinding, polishing), followed by assembling and mold trial.
- Outputs: New molds that meet defined quality criteria.
- Customers: The internal customer is the production department.

Current State Mapping (CSM)

The current process revealed a total lead time of 52 days, comprising 44.5 days of value-added (VA) activities and 7.5 days of non-value-added (NVA) and necessary non-value-added (NNVA) activities. This exceeds the company's mold development time target of 50 days, indicating a gap in meeting production quality objectives.

Process Activity Mapping (PAM)

Process mapping recorded 27 operation activities, 5 transportation activities, 8 inspections, no storage, and 8 delays. VA activities accounted for 28, NVA for 8, and NNVA for 13, highlighting the need to reduce inefficiencies in mold manufacturing.

Failure Rate Analysis

Based on the mapping results, value-added activities made up 53.85%, NNVA 25%, and NVA 15.38%. These indicate areas where process improvements are essential.

Waste Identification

DMAIC and VSM were used to identify waste in the mold production process from January to December. Six types of process failures were categorized into three primary types of waste: Defects, Inappropriate Processing, and Waiting.

- Defects: Functional locking failures, product flexibility mismatches, and mechanical issues in the mold.
- Inappropriate Processing: Delays in machining and repeated polishing due to inadequate results.
- Waiting: Delays due to unavailable machines for mold trials.

Measure Phase Analysis

1. Failure Rate Analysis via Pareto Diagram

The most frequent issue was machining time overruns (10 cases, 38.46%), followed by functional locking failures (8 cases, 30.77%), flexibility issues and machine unavailability (3 cases each, 11.54%), and mechanical and polishing delays (1 case each, 3.85%).

2. CTQ, Process Capability, DPO, DPMO, and Sigma Level

- CTQ: Six critical elements were identified, machining delays, locking failures, flexibility mismatches, machine unavailability, mechanical issues, and polishing delays.
- Process Capability: The overall Sigma level was 3.05322, which is within the average range for Indonesian manufacturing, but still leaves room for improvement.
- DPO (Defect Per Opportunity): Calculated at 0.0231 for the highest failure (machining delay).
- DPMO (Defect Per Million Opportunities): Equivalent to 23,148.
- Sigma Levels: Machining delays had a Sigma level of 3.493, and the overall average was 3.825.

Analyze Phase

1. Cause-and-Effect Analysis Using 4M (Man, Machine, Material, Method)

Each failure category was analyzed to identify root causes:

- Machining Delays: Lack of operator competence, poor discipline, overloaded schedules, unplanned maintenance, and miscommunication on instructions.
- Functional Locking Failures: Poor quality control, inadequate machine parameter settings, and incomplete drawings.
- Flexibility Issues: Inconsistent material density, poor parameter setting, and insufficient inspection.
- Machine Unavailability for Trials: Poor machine allocation planning, unanticipated production demands, and maintenance neglect.
- Mechanical Malfunctions: Lack of operator skills, incomplete SOP understanding, and incorrect material selection.
- Polishing Delays: Insufficient skills and tools, poor material quality, and complex polishing procedures.

Improve Phase

A. Improvement Proposals Using 5W+1H

1. Man:

- Provide training on instructions, discipline, and quality awareness.
- Assign responsible personnel for each mold.
- Conduct periodic supervision.

2. Machine:

- Improve setup instructions.

- Increase preventive maintenance from twice to three times annually.
- Use checklists for machine performance and process validation.

3. Material:

- Define agreed delivery schedules.
- Implement material inspection checklists.

4. Method:

- Train all employees on SOPs.
- Regularly audit work instructions and related documents.
- Standardize setup times.

Future State Mapping (FSM)

Key changes include:

- Reducing design and CNC programming times.
- Cutting setup times and eliminating non-value activities in CNC, milling, and polishing.
- Consolidating assembling and final inspection steps.
- Streamlining the mold trial process.

After implementing these improvements:

- VA activities increased to 90.4%,
- NNVA at 9.04%,
- NVA reduced significantly,
- Lead time reduced from 52 days to 44.25 days.

Control Phase

To sustain improvements:

1. Work Instructions: Simplify language and ensure correct implementation (e.g., CNC SOP).
2. Training: Schedule consistent employee development programs focusing on quality and responsibility.
3. Checklists: Ensure accuracy of materials, components, and tools delivered.
4. Preventive Maintenance: Increase frequency to three times a year.
5. 5S Audits: Conduct weekly audits by supervisors to monitor work area discipline. The control phase ensures that all improvements, from work procedures and training to material validation and maintenance, are institutionalized, supporting sustainable performance improvements in mold production.

Table 1. Comparison Before and After Improvement

No.	Process	VA (Before)	NVA (Before)	NNVA (Before)	VA (After)	NVA (After)	NNVA (After)
1	Design	11.50	0.50	2.00	11.00	0.00	1.25
2	CNC	7.25	0.50	1.50	6.50	0.00	0.75
3	Milling	6.50	0.25	0.25	6.00	0.00	0.25
4	Turning	1.00	0.25	0.25	1.00	0.00	0.25
5	Grinding	1.00	0.50	0.25	1.00	0.25	0.25
6	Polishing	9.25	0.00	0.50	8.25	0.00	0.25
7	Assembling	5.50	0.00	0.50	4.50	0.00	0.25
8	Trial	1.50	0.25	1.00	1.75	0.00	0.75
	Total	43.50	2.25	6.25	40.00	0.25	4.00

Total Lead Time (Before): 52.00 days

Total Lead Time (After): 44.25 days

Percentage (%) - Before: VA 83.65%, NVA 4.33%, NNVA 12.02% Percentage (%) - After: VA 90.40%, NVA 0.56%, NNVA 9.04%

From Table above, it can be seen that there was a reduction in the total lead time for mold production from 52 days to 44.25 days a decrease of 7.75 days. Additionally, the value-added (VA) percentage increased from 83.65% to 90.40%, a rise of 6.75%. This improvement clearly indicates that reducing waste in the mold-making process within the Mouldshop department is not only feasible but also significantly beneficial.

CONCLUSION

The mold-making process carried out revealed that the performance achievements were suboptimal. This shortfall was primarily due to process durations exceeding the targeted lead time. Based on the analysis using the DMAIC methodology, six (6) critical causes of failure were identified as significantly affecting the success of new mold development in the Mouldshop division. When these failure modes were mapped using the Value Stream Mapping (VSM) tool, they were classified into three main types of waste: defect, inappropriate processing, and waiting.

Root cause analysis using the Fishbone Diagram and the 4M framework (Man, Machine, Material, Method) highlighted several contributing factors:

Man: lack of operator competence, discipline, and initiative;

Machine: overloaded production schedules, equipment failures, machining errors, improper temperature control, and unstable machine precision;

Material: incorrect material selection and delays in procurement;

Method: inadequate implementation of work instructions, errors in machining processes, improper parameter settings, incomplete technical drawings, and complex process flows that were not clearly standardized.

To enhance the mold development process, a set of improvement proposals was developed using the 5W+1H tool within the DMAIC framework. These include: Refinement of machining work instructions and the establishment of standardized machine setup times. Adjustments to the preventive maintenance schedule, along with implementation of preventive maintenance checklists for each machine. Implementation of a verification column for actual conditions and responsible personnel (PIC) to ensure conformity of incoming materials, components, and tools. Structured training programs focused on work instruction compliance, employee responsibilities, discipline, initiative, and understanding of mold and product quality standards. Development of mold quality checklists for evaluating each mold produced. Routine supervision and auditing (via weekly 5S/5R inspections) by supervisors and foremen to ensure consistent implementation of process standards. Further optimization of process flow using a Future State Mapping (FSM) approach, which includes reducing process time, combining steps, and minimizing both NNVA and NVA activities.

Through the integrated application of DMAIC and VSM, the study successfully identified key inefficiencies and proposed practical measures that can significantly reduce lead time, increase the value-added ratio, and improve surface finish quality in plastic mold manufacturing. These findings offer a strategic foundation for continuous improvement and broader application in similar manufacturing environments.

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