

Application of Lean Six Sigma for Improving the Overall Equipment Effectiveness in a Semiconductor Company in the Philippines

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Abstract

This study utilized Lean Six Sigma to address the bottleneck process in a multinational semiconductor company in the Philippines. The overall equipment effectiveness (OEE) was used to identify the bottleneck process through the various components of OEE such as Availability, Performance, and Quality. In the Define phase, the lapping process with an OEE of 66.59% was identified as the process with the largest gap against the world-class target of 85%. In the Measure Phase, the sources of the gap are explored following the three (3) components - Availability, Performance and Quality, and its equivalent six big losses. It was found that the gap is attributed to Availability – set up and adjustment (0.51%) and equipment breakdown (1.19%), Performance – idling and minor stoppages (6.55%) and reduced cycle time (5.36%) and Quality – quality loss (2.40%) and reduced yield (1.12%). In the Analyze phase, the root causes of the six big losses were identified and validated such as high change plate downtime, high unplanned downtime, variation in loading and unloading time, variation in machine lapping time, no lots available, use of excess tools for production, wrong execution of rework distribution and high abort rate. In the Improve phase, solutions to address the validated root causes were implemented such as application of SMED concept to the planned downtime, autonomous maintenance to sources of unplanned downtime, best practice sharing in standardize loading and unloading time, mistake proofing for machine lapping time, tool management system application to address the use of excess tools during production, mistake-proofing in loading rework items to non – rework tools and optimizing lapping process machine recipe to reduce abort rate. In the Control phase, FMEA was used to identify the risks and establish the right control measures such as control charts and dashboards. The results of the study showed a significant OEE improvement (p -value = 0.000) in the lapping process from 66.59% to 85.09%. The results were enabled by the importance of data availability, the use of quantitative tools in the project, and the use of controls and prioritization in project implementation. These findings can be used as a benchmark in deploying OEE improvement projects in the semiconductor industry and other manufacturing industries.

Keywords

Overall Equipment Effectiveness, Lean Six Sigma, Process Improvement, Manufacturing Excellence

1. Introduction

Manufacturing firms focus on productivity improvements to survive in the competitive marketplace because a high productivity performance has a direct relationship with the equipment efficiency and process control (Azizi, 2015). One way to measure equipment efficiency is through the overall equipment effectiveness (OEE) which has been widely used as a quantitative tool essential for the measurement of productivity in manufacturing industries. The application of OEE is to identify and eliminate the related losses to improve the performance and reliability between facilities (Heng, Aiping, Liyun & Moroni, 2019). Based on the practices in complex manufacturing systems, OEE is an effective tool to identify system bottlenecks such as uncertainties of stoppage duration, production speed, and quality losses (Tang, 2019; Heng, et al., 2019).

As OEE is an important performance measure for the effectiveness of any equipment, careful analysis is required to know the effect of various components such as Availability, Performance and Quality (Relkar & Nandurkar, 2012). On the complexity of using performance measures, enhanced and sustained production improvement capability can be achieved by combining OEE with other process improvement tools and techniques (Andersson & Bellgran, 2015). The use of Failure Modes and Effects Analysis (FMEA), Statistical Process Control (SPC), Autonomous Maintenance

(AM), Single Minute Exchange of Dies (SMED) and Design of Experiments (DOE) is strongly recommended to improve the production productivity performance for the manufacturing industry (Relkar et al., 2012; Vijaya, et. al., 2014; Azizi, 2015; Baghbania, et al., 2019). Another approach involves reviewing the present planning and scheduling methodologies, identifying bottlenecks, reducing change over time, and reducing work in progress (WIP) in the production line (Kumar, Mani & Devraj, 2014).

Lean Six Sigma (LSS) is a systematic approach to improvement needed to improve performance as measured by quality, cost, delivery, and customer satisfaction. It is one of the latest generations of improvement approaches being used both by manufacturing and service industries (Ozcelik, 2010). Lean Six Sigma is a business strategy and methodology that increases process performance resulting in enhanced customer satisfaction and improved bottom-line results (Snee, 2010). In the past decade, the marriage between Lean and Six Sigma made an important excellent system in addressing problems on the shop floor (George, 2002). Lean focuses on identifying and eliminating wastes in the process and Six Sigma focuses on process variations resulting to poor quality following the DMAIC (Define – Measure – Analyze – Improve – Control) pattern (Alata, 2020; Anand, et al., 2010; Azizi, 2015; Costa, Lopes & Brito, 2019; Priya, Jayakumar & Kumar, 2019). The performance of manufacturing companies is driven by market share gains, higher profit/margins, and higher product performance versus the competition. Improving these key factors drives revenues and earnings, lowers unit costs, and stimulates greater enthusiasm for products and support. This translates the need for process improvements as measured by manufacturing process efficiencies measured based on industry benchmarks or world-class standards (Islam, 2019).

The proponent company is a multinational semiconductor company located at CALABARZON. Its main products are sub-assembly parts of storage devices shipped to Thailand for assembly as the final product. Lean Six Sigma is being practiced by the organization since 2010 and was able to generate significant cost reduction initiatives from process improvement projects completed. Driven by the increasing competition due to the demand fluctuation in the semiconductor industry, the management decided to utilize Overall Equipment Effectiveness (OEE) as one of the metrics of their manufacturing efficiencies. The actual calculated process OEE ranges from 60.0% to 75.0% and falls short to the World Class Standard of 85.0% (Nakajima, 1989). This gap versus the world-class standard of 85% translates to a US \$30 million annualized opportunity validated by the Finance and Cost Management teams of the company. The cost reduction opportunity includes capital avoidance of not buying the additional machine, reduction of maintenance and spare parts, an increase in the utilization of machines, reduction in inventories, and reduction of scrap and rework rates.

This study applied the Lean Six Sigma approach in improving the OEE of the process that has the largest gap against the world-class target of 85.0% and checked its effectiveness of applying Lean Six Sigma tools and techniques based on the results. This study helped the proponent company in achieving its objective of operating more efficient manufacturing processes which translated to significant improvements in having higher machine availability, increased process performance, and improved quality (Chiarini, 2015). The successful application of Lean Six Sigma in improving the lapping process OEE provided the organization a framework on how to replicate the gains acquired from the implementation of this study. This study covered the identification of problem areas based on OEE up to the deployment of sustenance or control methods following the DMAIC approach applied to the lapping process.

2. Methodology

This study utilized the Overall Equipment Effectiveness (OEE) concepts as suggested by Nakajima (1989) integrated to the Lean Six Sigma's DMAIC (Define – Measure – Analyze – Improve – Control) approach to improve process efficiency and effectiveness as demonstrated in the studies of Chiarini (2015) and Azizi (2015). Following the summarized and integrated findings from several related pieces of literature, this is how the DMAIC framework has been adopted to this OEE improvement study.

2.1 Define Phase

In Define Phase, an overall improvement project team was created to apply the approach to the bottleneck process identified with the largest gap versus the world-class target of at least 85% (Tang, 2019 & Nakajima, 1989). Baseline OEE for the chosen process was reviewed using a histogram and summary statistics to check the current capability of the process and used to set a realistic target (Azizi, 2015 & Chiarini, 2015). A SMART objective was set based on the gathered historical data (Ozcelik, 2010 and Snee, 2010). Based on the historical data and other related information sources, a project charter was completed to cover critical information to initiate the project such as business case, problem statement, control chart for the lapping process OEE, objective statement, project scope, project timeline,

consequential metric, project benefits, project team, and project approvers. A SIPOC diagram was created to show the scope and/or boundaries of the project. (Ozcelik, 2010 and Snee, 2010).

2.2 Measure Phase

In the Measure Phase, the OEE baseline of the lapping process was reviewed based on the components Availability, Performance, and Quality and the contribution of the six big losses (Lanke et al., 2016; Aman et al., 2017 & Perdana et al., 2018). The project team performed historical data analysis and work sampling activities to validate the existence of the identified gap from the six big losses of OEE. A table was created to summarize each identified source of the gap to be used (Baghbani et al., 2019 & Foulloy et al., 2018) as an input to the Analyze phase. Quick wins were generated based on the results of the conducted Gemba walks and solicited input from stakeholders (Puvanasvaran et al., 2013 & Priya et al., 2020).

2.3 Analyze Phase

In the Analyze Phase, the identified six big losses under Availability, Performance, and Quality components were prioritized based on their estimated OEE impact (Indrawati et al., 2015; Pugna et al., 2016 & Baghbani et al., 2019). Prioritized six big losses were further investigated using why – why analysis (Azizi, 2015; Chiarini, 2015; Aman et al., 2017 & Priya et al., 2020). Validation activities were done using graphical analysis tools such as box plot, Pareto chart, and statistical hypothesis testing techniques such as ANOVA, 1 sample t-test, 2 sample t-test (Pzydek, 2003; Kumar et al., 2016 & Baghbani et al., 2019).

2.4 Improve Phase

In the Improve Phase, improvement action items were implemented, tested, and evaluated based on its effectiveness. Improvement tools include Autonomous Maintenance (Azizi, 2015), SMED (Kumar et al., 2014; Chiarini, 2015; Kumar et al., 2016; Sousa et al., 2018); cycle time improvement and other improvement strategies integrated to the domain expertise of the project team about the process like work standardization and mistake proofing.

2.5 Control Phase

In the Control Phase, control measures were established and standardized for compliance and sustenance of gains. An FMEA was created as a guide for identifying risks and creating control measures for the implemented improvements (Pzydek, 2003). Control charts (Azizi, 2015) were created and deployed using a dashboard utilizing emerging technologies such as Minitab and Tableau (Bhattacharjee et al., 2019).

Table 1 shows a summary of the tools and tasks required to be delivered by the project team to achieve the objectives for each of the phases of the DMAIC methodology.

Table 1: OEE Lean Six Sigma DMAIC Approach Framework

Phase	Objective	Tools	Task
Define	To define the problem (gap) and goal of the project.	<ul style="list-style-type: none"> ▪ OEE ▪ SMART Objective ▪ Project Charter ▪ SIPOC Diagram 	<ol style="list-style-type: none"> 1. Define the baseline OEE. 2. Write the problem and goal statement. 3. Complete the project charter. 4. Set the project boundaries using the SIPOC Diagram.
Measure	To measure the current performance of the chosen process and establish the sources of the gap.	<ul style="list-style-type: none"> ▪ Six Big Losses <ul style="list-style-type: none"> ○ Availability <ul style="list-style-type: none"> ○ Set up & adjustments ○ Equipment breakdown ○ Performance <ul style="list-style-type: none"> ○ Idling & minor stoppages ○ Reduced speed ○ Quality <ul style="list-style-type: none"> ○ Quality losses ○ Reduced yield ▪ Work Sampling ▪ Graphical Analysis ▪ GEMBA Walk ▪ Quick Wins 	<ol style="list-style-type: none"> 1. Check the historical data of Availability, Performance and Quality and the equivalent six big losses to establish sources of OEE gap. 2. Conduct work sampling and GEMBA walk to validate existence of the six big losses. 3. Create a tree diagram following the Six Big Losses of OEE based on the results of the gap analysis. 4. Generate list of quick wins to capture low hanging fruits to improve OEE.
Analyze	To analyze the results of measurements and determine the valid root causes of the problem.	<ul style="list-style-type: none"> ▪ Why – Why Analysis ▪ Graphical Analysis ▪ Statistical Hypothesis Testing 	<ol style="list-style-type: none"> 1. Prioritized sources of Six Big Losses based on its impact to OEE, if necessary. 2. Investigate the potential causes of prioritized source of Six Big Losses using Why – Why analysis. 3. Validate potential root causes using graphical and hypothesis testing tools and techniques.
Improve	To improve the process and implement the changes.	<ul style="list-style-type: none"> ▪ Single Minute Exchange of Die (SMED) ▪ Autonomous Maintenance ▪ Work Standardization ▪ Cycle Time Improvement ▪ Mistake Proofing 	<ol style="list-style-type: none"> 1. Develop and test the best solution and design the implementation plan. <p>Availability</p> <ul style="list-style-type: none"> ○ SMED to reduce time for set up & adjustments ○ Autonomous Maintenance to reduce occurrence of equipment breakdown. <p>Performance</p> <ul style="list-style-type: none"> ○ Work standardization to address idling & minor stoppages ○ Cycle time improvement to address reduced speed <p>Quality</p> <ul style="list-style-type: none"> ○ Mistake proofing to reduce quality losses
Control	To control the improved process and monitor the results.	<ul style="list-style-type: none"> ▪ FMEA ▪ Control Charts ▪ Visual Management / Dashboards 	<ol style="list-style-type: none"> 1. Document standardization by revising work standards. 2. Establish monitoring of improvements following the Process Control Plan. 3. Set up Control Charts and dashboards to monitor the process performance. 4. Transfer the ownership to the process owners.

3. Results

The result of DMAIC applied to the lapping process increased OEE from 66.59% to 85.09% and improved daily output production from 59 DGR to 66 DGR which is an 11.86% improvement. The success of the project was achieved by following the structured approach of the DMAIC methodology integrated with the OEE framework. The right problem was identified and prioritized during the Define phase. In Measure Phase, the sources of the gap were determined and accounted based on six big losses of OEE using historical data analysis, GEMBA walk, work sampling, and input from stakeholders. Significant factors were pinpointed and validated in the Analyze phase using root cause analysis, graphical and hypothesis testing tools, and techniques. Sustainable solutions were implemented together with deployed control mechanisms in the Improve and Control phases. The details for each phase are discussed in the succeeding parts of this section. The result of each phase in DMAIC is summarized as shown in Table 2.

Table 2. DMAIC based OEE Improvement Approach Results

Phase	Objective	Analysis Tools	Results
Define	To define the problem and goal of the project.	<ul style="list-style-type: none"> ▪ OEE ▪ SMART Objective ▪ Project Charter ▪ SIPOC Diagram 	Set an objective to increase the lapping process OEE from 66.59% to 85.00% which is a 27.65% improvement by the end of June 2020.
Measure	To measure the current performance of the chosen process.	<ul style="list-style-type: none"> ▪ OEE's Six Big Losses ▪ Gap Analysis ▪ Work Sampling ▪ Tree Diagram ▪ GEMBA Walk ▪ Quick Wins 	There is an 18.41% OEE gap accounted to Availability of 2.26% (87.74% vs 90%), Performance of 14.46% (80.54% vs 95%) and Quality of 5.01% (93.99% vs 99.00%).
Analyze	To analyze the results of measurements and determine the valid root causes of the problem.	<ul style="list-style-type: none"> ▪ Why – Why Analysis ▪ Graphical Analysis ▪ Hypothesis Testing 	Identified and validated root causes are idling and minor stoppages (7.59%), reduced cycle time (6.51%), quality losses (3.41%), reduced yield (1.60%), equipment breakdown (1.58%) and set up and adjustment (0.69%).
Improve	To improve the process and implement the changes.	<ul style="list-style-type: none"> ▪ Single Minute Exchange of Die (SMED) ▪ Work Standardization ▪ Mistake Proofing ▪ Cycle Time Optimization 	OEE improvement from 66.59% to 85.09% is significant (p value = 0.000 vs $\alpha = 0.05$).
Control	To control the improved process and monitor the results.	<ul style="list-style-type: none"> ▪ FMEA ▪ Control Charts ▪ Visual Management / Dashboards 	Control methods and dashboard system to monitor and sustain the gains were deployed.

3.1 Define Phase

The proponent company for the study is a multinational semiconductor company that produces parts of storage devices. There is an increasing demand for the manufactured parts due to the increasing need for storage devices globally translated to a 22.43% increase in quarterly demand for the company. With the continuous increase in demand, there will be additional machines to be acquired. To remain cost-competitive and avoid capital expenditure, top management decided to launch an initiative to use OEE as a framework to assess process efficiencies. OEE was chosen as the framework because of a benchmark made from a similar business utilizing the approach. The application of OEE is expected to reduce costs and achieve capital cost avoidance.

After determining the current OEE performance of the lapping process, a project charter was established to initiate the project containing the important project details below.

- a. Business Case: To support the strategic initiative of ensuring value creation for the company, the Lean Six Sigma project to improve OEE for critical processes was started and supported by the Top Management. As identified in the gap analysis, the lapping process will be the focus of the project.
- b. Problem Statement: There is a low Lapping process OEE of 66.59% from August 2019 to December 2019 versus the World Class Target of 85.0% which is a gap of 18.41%.
- c. SMART (Specific, Measurable, Attainable, Repeatable, and Time-Bound) Objective Statement: To increase lapping process OEE from 66.59% to 85% which is a 27.65% improvement by the end of June 2020.
- d. Project Benefits: This project has a value of USD 30M per year.

To establish the project scope, a SIPOC diagram of the lapping process project was created. The team identified all the elements required such as suppliers, inputs, processes, outputs, and customers of the lapping process. The supplier of the process is the pre – lapping process (crib) supplying the quads and which go through the process activities from loading to claim station giving the output row bars to the next process which is the advanced lapping. The project focused on the Lapping process concerning dependencies on Wire Bond and Row Slice processes for the input requirements.

3.2 Measure Phase

In the Measure Phase, the team checked the current system and established the sources of gap per OEE components Availability, Performance, and Quality. The sources of the gap in the lapping process OEE was taken from historical data and work sampling. The project team was able to understand the baseline of the three (3) OEE components Availability, Performance and Quality, and their equivalent sources following the six big losses. A summary table showing the gap and corresponding sources is provided in this phase and is used as an input for the Analyze phase. The project team conducted a Gemba walk and solicited inputs from the process stakeholders to look for potential quick wins that will address low hanging fruits to improve the lapping process OEE.

3.2.a Gap Analysis for Availability

The team checked the actual data distribution of the Availability components set up and adjustments and equipment breakdown from August 2019 to December 2019 database. Change plate downtime is at an average of 53.77 minutes which exceeds the target of 34.00 minutes resulting in a 19.77-minute gap or a 0.69% decrease in Availability. On the other hand, equipment breakdown loss is at an average of 135.46 minutes which exceeds the target of 110.00 minutes resulting in a 26.46-minute gap or a 1.58% decrease in Availability.

3.2.b Gap Analysis for Performance

Work sampling is a method of where workers are observed at random times and their activities recorded (Everhart, 1997). The project team agreed to conduct a work sampling for the lapping process. They have selected machines that represent the average OEE performance and subjected them to work sampling. It was a full day set up where engineers conducted a work sampling on the lapping process and recorded the time for each activity done within the 24-hour observation. From the work sampling, the team found out that the lapping process Performance is only at 78.27% (987 minutes operational against 1,261 minutes available) which is a gap of 9.46% against the target of 95%. The gap was accounted for idling and minor stoppages loss of 7.95% due to idle time between loading (no lots, no operator, and no materials) and reduced cycle time loss of 6.51% based on work sampling results.

3.2.c Gap Analysis for Quality

Figure 5 shows the baseline distribution of Quality data. None of the daily Quality data is meeting the World Class Target of 99%. Based on the summarized data from the Process Engineering section, the 5.01% gap is accounted to quality loss of 3.41% and reduced yield of 1.60%

3.2.d Summary Table of Identified Gap Using OEE Six Big Losses

From the OEE component gap analysis conducted for Availability, Performance, and Quality, a summary of results is presented in Table 3. The 18.41% OEE gap is accounted to Availability of 2.26% (87.74% vs 90%), Performance of 14.46% (80.54% vs 95%) and Quality of 5.01% (93.99% vs 99.00%). The Availability gap of 2.26% is accounted for to set up and adjustments of 0.69% and equipment breakdown of 1.58%. The Performance gap of 14.46% is accounted for idling and minor stoppages of 7.95% and reduced cycle time of 6.51%. The Quality gap of 5.01% is accounted for quality losses of 3.41% and a reduced yield of 1.60%. The root causes of these gaps based on the six big losses were further explored in the Analyze Phase.

Table 3. Summary Table of Identified Gap Using OEE Six Big Losses

OEE = A x P x Q 66.59% vs 85.00% Gap = 18.41%	Availability (A) 87.74% vs 90% Gap = 2.26%	Set Up & Adjustments 0.69%
		Equipment Breakdown 1.58%
	Performance (P) 80.54% vs 95% Gap = 14.46%	Idling & Minor Stoppages 7.95%
		Reduced Cycle Times 6.51%
	Quality (Q) 93.99% vs 99%	Quality Losses 3.41%
		Reduced Yield 1.60%

From the finding and results of the gap analysis conducted such as historical data analysis and work sampling, the team conducted a GEMBA walk to look for quick wins. GEMBA walk is the practice of visiting and observing the actual workplace to check the actual condition of the process. After a successful team GEMBA walk, a session was called together with the stakeholders to better understand the observed findings and to generate and identify some quick wins. The generated list of quick wins is given below.

- Correction of entries of planned and unplanned downtime activities in the system
- Provision of visual management to identify the status of lots in the inventory racks
- The setting of replenishment schedule for chemical supply
- Sharing of best practices among operators, technicians, and engineers
- Creation of monitoring for six big losses factors without an existing database for proper accountability of action items

3.3 Analyze Phase

They identified six big losses of the lapping process from the Measure phase were further explored using root cause analysis tools and validated using graphical and statistical hypothesis testing in the Analyze phase. Table 4 was used by the team to simulate the expected gain from addressing each source of the gap from the activities in Measure Phase. Each loss was added to each component as they were projected to be addressed and the new OEE is calculated. The top contributors of OEE gain were idling and minor stoppages, reduced cycle time, quality loss, and equipment breakdown. As per the direction of the top management, different sub-project teams will be accountable for every six big losses to achieve 85%. This means that all six big losses will be addressed at the same time.

Table 4. Expected OEE Gain Matrix

OEE Components	Baseline	Six Big Losses	From	To	OEE Gain	Rank
Availability	87.74%	Set up & Adjustment	66.42%	66.93%	0.51%	6
		Equipment Breakdown	66.42%	67.61%	1.19%	5
Performance	80.54%	Idling & Minor Stoppages	66.42%	72.97%	6.55%	1
		Reduced cycle time	66.42%	71.78%	5.36%	2
Quality	93.99%	Quality loss	66.42%	68.82%	2.40%	3
		Reduced yield	66.42%	67.54%	1.12%	4

3.3.1 Set Up and Adjustment (Change Plate Downtime) under Availability

Change plate is the planned maintenance activity done when the plate used for lapping reaches the set useful life or if there are process anomalies detected and requires performing one. Using the SMED worksheet as a guide, the team was able to identify the wastes associated with the excess time of 19.77 minutes for the change plate. The team also identified if there are process steps that can be converted from internal (done within the change plate activity) to external (done outside the change plate activity such as material preparation, etc.). The team identified getting the materials to be used change plate and the actual preparation of a plate to be used can be converted into external process steps and will result in a change plate downtime reduction. Recommended actions for the identified wastes were generated by the team.

3.3.2 Equipment Breakdown (Top Unplanned Downtime Contributors) under Availability

Based on the Pareto analysis conducted, the top detractors causing the unplanned downtime are servo drivers, hose, plunger, and squeegee assembly. Upon validation that there is no significant difference (p -value = 0.412) in the repair time across the technicians, the team focused on lowering the occurrences of the top detractors. Using why – why analysis performed with the technicians and engineers of the process identified the following root causes for each top detractor: servo driver - high downtime of servo controller/driver due to use of obsolete parts; hose - accumulation of pump and hose problem due to non-inclusion in PM checklist; plunger and squeegee assembly: - due to wrong handling of plunger and assembly while performing change plate.

3.3.3 Reduced Cycle Time (Loading and Unloading Time) under Performance

Time studies were conducted to both new and tenured operators performing the handling (loading and unloading) at the lapping process and results were tested using a 2-sample t-test. The 2-sample t-test showed that the difference in handling between new and tenured operators is significant (p -value = 0.000). The new operators perform that task slower than the tenured ones resulting in longer cycle time and lower Performance and OEE for lapping process OEE

3.3.4 Reduced Cycle Time (Lapping Process Time) under Performance

About 90% of the total lapping process time is accounting for machine lapping time. An excess of variation in machine lapping time affects the Performance and OEE significantly. This was proven by the team by comparing the machine lapping time applied to each tool exploring the by model variation. The team collected the actual lapping time set in each machine by model. ANOVA test results showed that there are a significant difference and variation in the set lapping process time per model/tool against target lapping time of 16 minutes. Using a why – why analysis, the team investigated the root cause for such variation.

3.3.5 Reduced Cycle Time (No Lots Available) under Performance

Using the average daily going rate of the complementary processes in the line, the project team validated that there is a significant difference in their output capacity (p -value – 0.000). This is due to the current capability of the slicing process – the supplying process inside the production line configuration. The team looked at the flow of the input and lead to the validation in the actual number of tools used against what is required. This is discussed in 3.3.6. Reduced Cycle Time (Use of Excess Number of Tools) under Performance.

3.3.6 Reduced Cycle Time (Use of Excess Number of Tools) under Performance

The 2 – proportion test showed that tools are being used more than what is required or based on what is calculated. In the current system, at a 58 DGR output requirement, 140 tools are being operated as against the requirements of 137. Having the ideal number of tools to be used, it shows that at 6 DGR output requirements, the company only needs to run 127 tools. The use of excess tools resulted in a loss in the Performance of the lapping process machines. Instead of a machine producing at its full performance capacity, it is given in other machines that waste resources including manpower, utilities, chemicals, and spare parts. This excess use of tools also results to lower OEE due to lower lapping process Performance.

3.3.7 Quality Loss (Rework Item Distribution) under Quality

The rework data from August 2019 to December was compared across tools and used boxplot and ANOVA to check if rework items are only processed on assigned rework tools. Upon validation, rework items are being processed even in unassigned machines for rework (p -value = 0.000). This results in the contamination of new inputs from rework items processed. The team investigated the root cause of this event even it is already included in the process of engineering guidelines. By current process design, operators can load rework items to non – assigned rework tools. The team communicated these results to the process engineering department and agreed to create a system that will scan lot identification before actual loading that will prevent the loading of rework items in non – assigned rework tools.

3.3.8 Reduced Yield (Abort Rate) under Quality

Yield is an important manufacturing parameter and is one of the six big losses of OEE under Quality. In this study, the abort rate is the source of yield loss and is dependent on the design of the input material supplied by the parent company. Material design is under optimization and the team focused on other root causes identified such as passive

lapping, user-initiated abort, and plate crash. Passive lapping is due to the unoptimized machine program, user-initiated abort is due to the difference in understanding of process status by the users, and plate crash is related to the change plate activity. There are only quick wins that can be applied, and this issue will only be addressed through material design and is not feasible within the scope of the project.

3.4 Improve Phase

In the Improve phase, improvement action items were implemented based on the validation root causes from the Analyze phase. Improvement tools such as Single Minute Exchange of Dies (SMED), Autonomous Maintenance (AM), work standardization, cycle time improvement, mistake proofing, and other improvements integrated with process domains.

3.4.1 Summary of Improvement Action Items Deployed to Lapping Process and the OEE Results

The improvement action items deployed are the integration of SMED, autonomous maintenance, works standardization, and mistake-proofing to the domain expertise of the lapping process.

Table 5 shows the results of the improvement of action items based on validated root causes of OEE losses following the six big losses approach. Shown in the boxplots are a comparison of the before and after improvements measures of OEE and its three (3) components, Availability, Performance, and Quality. With all the improvements applied, the lapping process OEE significantly improved (p-value = 0.000) from 66.59% to 85.09% which is a 27.78% improvement. All improvements are significantly based on the improvement percentages of 6.62%, 16.24%, 3.40%, and 27.78% for Availability, Performance, Quality, and OEE, respectively.

Table 4. Before and After Results of Lapping Process OEE

Items	Before	After	% Improvement	P - Value
Availability	87.74%	93.54%	6.62%	0.000
Performance	80.54%	93.61%	16.24%	0.004
Quality	93.99%	97.18%	3.40%	0.000
OEE	66.59%	85.09%	27.78%	0.003

3.5 Control Phase

To sustain the improvements of the deployed solutions in Improve phase, the control measures were established in the Control phase. An FMEA was created to assess potential failures for the identified critical factors in the project. Statistical process controls (SPC) were also provided for both OEE and validated critical factors. Visual management using dashboards were part of the team's recommended control measures that will allow process owners to check the lapping process OEE on a real-time basis.

The team used FMEA to assess the potential failure related to the validated six big losses and the risks associated with them. Potential failures were identified, and their corresponding Severity, Occurrence, and Detection were scored to determine the Risk Priority Numbers (RPN). A modified scoring matrix was created by the team for this OEE improvement project aligned with the existing scoring matrix used by the organization as shown in Table 10. The presented modified scoring matrix was used to complete the FMEA shown in Table 8. RPNs will be the basis to assess if there are high risks that need to be addressed concerning the lapping process OEE.

As a result of the use of FMEA, control charts were established as a control method not only for OEE but for the identified six big losses. Data from the OEE database are linked to Minitab and Tableau and will update on a real-time basis. This will provide process owners of insights on how to manage the lapping process and to execute contingency actions in case the target OEE is not being met.

4. Discussion

The application of Lean Six Sigma on the OEE project plays a critical part by giving a structured approach on how to achieve the 85% OEE world-class target. The integration of Lean Six Sigma to the OEE approach paved the way for the identification of the source of six big losses of OEE and the application of the right solutions that addressed those sources. In this study, the application of Lean Six Sigma integrated with the OEE approach resulted in a significant improvement (p-value of 0.000) of 27.78% from 66.59% to 85.09% OEE for the lapping process. The success of the implementation of the integrated DMAIC and OEE framework in this study can be the basis of the succeeding OEE projects for the company and the semiconductor industry.

4.1 The importance of data availability in using Lean Six Sigma

Before OEE can be used as an effective productivity measurement and improvement approach integrated into a data-driven approach like Lean Six Sigma, data availability is critical. Data availability will enable the identification of bottleneck processes, highlight improvement opportunities, validate significant factors affecting the problem, and evaluate the effectiveness of the solutions implemented throughout the DMAIC approach. In a Lean Six Sigma project, data availability is a key enabler to the success of its implementation. Without available and reliable data, decision making will be weaker leading to failure in achieving the project objectives. Organizations that want to use Lean Six Sigma integrated with OEE must create a process management system that will capture and report all the OEE relevant data and utilize in their OEE process improvement using the DMAIC approach.

4.2 The use of quantitative tools in implementing Lean Six Sigma

Implementing Lean Six Sigma requires the use of several tools such as gap analysis, work sampling, GEMBA walk, root cause analysis, graphical analysis, statistical hypothesis testing, SMED, work standardization, optimization techniques, mistake proofing, visual management, statistical process control, and FMEA. Companies without the capacity or knowledge of these tools cannot just implement Lean Six Sigma. The right utilization of the essential Lean Six Sigma tools in each phase of DMAIC is critical to the success of the OEE project. The involvement of all stakeholders of the lapping process from operators to managers from cross-functional departments made the utilization of Lean Six Sigma tools more efficient and the generation of improvement action more systematic and holistic resulting in significant positive changes.

4.3 The use of controls and prioritization in project implementation

Applying an appropriate quality management strategy such as Failure Mode and Effect Analysis (FMEA) plays an important role in determining the risks and appropriate improvement method for controlling the reoccurrence and magnitude of six big losses of OEE. The application of Lean Six Sigma has improved OEE but the identification of controls and RPN can provide information to management on what project to prioritize in terms of maintaining the current improved OEE level. FMEA helped the team to identify and prioritize the potential failure mechanisms related to the six big losses of the lapping process OEE. With the potential failure mechanisms identified, FMEA was used as the basis of the process control plan on how to sustain the OEE gains acquired from the implementation of the improvement action items. An FMEA uses RPN to assess risk in three categories: Occurrence (O), is the assessment of how frequently the specific failure cause is projected to occur, Severity (S), is an assessment of the seriousness of the effect of the potential failure to the system and its surroundings, and Detection (D), such as the assessment of the probability that the operating parameters monitoring system will detect a cause/mode of failure before the component is damaged and stopped (Scipioni et al., 2002). Thus, RPN represents the seriousness of potential risks critical to reliability, the safety of systems, or productivity of process (Seung and Kosuke, 2003). The RPN for every six big losses was identified and became the basis of improving the control measure currently being applied in the lapping process. The team generated recommended actions to reduce the RPNs calculated from the FMEA. A re-assessment was made by the team after the implementation of the recommended prevention and detection control methods and showed considerable reductions on the RPNs of the top six big losses sources for the lapping process. Mistake proofing on machine programs, control charts for OEE and its components, visual management, and Tableau dashboard displayed in production areas were deployed in the lapping process which helped stakeholders assess operational risks and help in decision making (Bhattacharjee et al., 2019).

5. Conclusion

This study was implemented in a multinational semiconductor company which demonstrated how OEE can be improved using the Lean Six Sigma methodology including other statistical tools and techniques. The study used the DMAIC approach and the OEE concepts was applied including its components such as Availability, Performance, and Quality. In the Define phase, the project team identified the lapping process as the focus process using gap analysis. Sources of the gap and their contribution to the 18.41% lapping process OEE gap were identified in the

Measure phase with the use of historical data baselining, work sampling, GEMBA walk, input from stakeholders, and tree diagram. With the use of why – why analysis, FMEA, graphical and statistical analysis, root causes are generated, prioritized, and validated in the Analyze phase. Improvements were realized in the Improve phase with the help of SMED, work simplification, visual management, mistake proofing, and optimization techniques resulting in a significant (p -value = 0.000) 27.78% lapping process OEE improvement from 66.59% to 85.09%. Control measures were identified and deployed using FMEA, control charts, and operational dashboards in the process.

The success of the study is accounted for to utilization of the integrated Lean Six Sigma and OEE approaches with important considerations to three major findings. These three major findings in this the Lean Six Sigma study are the importance of data availability, the use of quantitative tools in the project, and the use of controls and prioritization in project implementation. The findings demonstrated in this study paved the way for the utilization of Lean Six Sigma in OEE improvement projects that yielded significant improvements. These findings can be used as a benchmark in deploying similar projects in the semiconductor industry and other manufacturing industries.

Future research can replicate the use of the combined Lean Six Sigma and OEE framework and apply it to other manufacturing industries to check its effectiveness. Specific tools might also change depending on the complexity and nature of six big losses of the identified focus process. Additional key enablers can also be explored to check its impact on the results of the implementation of the framework.

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