# Improving Metrology Fleet KPIs for Advanced Foundry Manufacturing

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**Abstract – In semiconductor manufacturing, the time it takes for wafers to process through the line is of utmost importance. Any delay in the processing of these wafers is very costly to the foundry and the end customer. Cycle time is one of the key metrics that any customer looks for in a foundry to ensure that their products are delivered on schedule. To improve overall cycle time, every equipment fleet needs to consistently and efficiently process wafers. In this paper, we will demonstrate sustainable improvements to key manufacturing metrics on Nova OCD fleet. The key metrics discussed are lot holds, recipe FTR (First-Time Right), fleet availability and fleet matching. Areas of improvement were analyzed, based on which an improvement strategy was developed and executed for each of the metrics. Weekly tracking of the respective metrics showed that the action plan was successful and sustainable. Similar approach could be applied to any metrology fleet to further improve manufacturing metrics.**

**Keywords: manufacturing efficiency, fleet availability, scatterometry, wafer-less recipe, pattern recognition, fleet matching**

## I. Introduction

In any lean manufacturing environment, operation efficiency and low cycle times are critical. With the increasing number of scatterometry steps in advanced technology nodes with various innovations [1, 2, 3], there is a significant contribution of metrology measurement efficiency to overall cycle time. Key Performance Indicators (KPIs) to assess such efficiency are especially critical in a foundry environment, given the high number of products manufactured for any given technology node. As the foundry fab transitions to advanced technology nodes, continuous improvement in fleet performance is required to ensure the fleet meets the metrology budgets for the advanced processes [4].

In this paper, we focused on 4 key manufacturing metrics to further improve the metrology measurement efficiency of the Nova OCD fleet. These 4 metrics are lot holds, recipe First Time Right (FTR), fleet availability and fleet matching.

Lot holds are represented as a percentage of failures over total number of lots measured on the fleet, and is a direct measure of the recipe creation quality. Recipe FTR is an indicator of the robustness of the wafer-less recipe creation methodology. Fleet availability reflects the uptime of the fleet and is one of the indicators of software and hardware stability. Fleet Matching Precision (FMP) is the measure of measurement variation across the fleet. These metrics were tracked weekly and performance over time demonstrated sustainable improvement of the metrology measurement efficiency of the fleet, some beyond initial target.

## II. Data Analysis and Action Plan

Once the key manufacturing metrics were defined, long term targets were set for each metric to further improve the fleet. Structured Problem Solving (SPS) methods were employed to systematically drive improvements. At the start, 13 weeks of data were analyzed to identify areas of improvement and investigation of contributing factors was carried out. Based on the analysis results, a strategy was devised for each metric to achieve individual targets. The changes addressed contributing factors and possible root causes in order of criticality as well as ease of implementation.

### *A. Lot Holds*

A "Lot Hold" is a temporary stop applied to a unit of production inventory called a 'Lot'. While there are many types of lot holds, they all generally indicate a signal of some non-conformance or inconsistency that must be addressed before the lot continues the production cycle. 'Cycle Time' (CT) can be defined as the total 'Process Time + Wait Time' from wafer start to fab out. 'Wait time' is anything that is not process time. This mostly falls into two categories: necessary non- process related items, such as transportation and metrology, and waste items, such as re-measurements, reworks, white space (for example when a lot is waiting at a stocker or waiting for a tool to be available, for a process job to be assigned…etc), and lot holds. As such, lot holds will add directly to the cycle time of a lot. If you have a lot hold that takes three hours to disposition, all other things being equal, that's three hours longer the lot will take to complete all processing.

Fig. 1 and Fig. 2 describe two simple models of lot hold impact in metrology. Fig. 1 is the cumulative impact in days as a function of wafer starts (or steps executed per week) and hold%. Hold% is a normalized key performance indicator (KPI) where the number of holds is divided by the number of total opportunities. Fig. 2 is the cumulative impact in days seen by a typical lot as a function of hold% and lot sampling rate. These models do not take into account other factors like re-measurements/rework waste, lot hold disposition

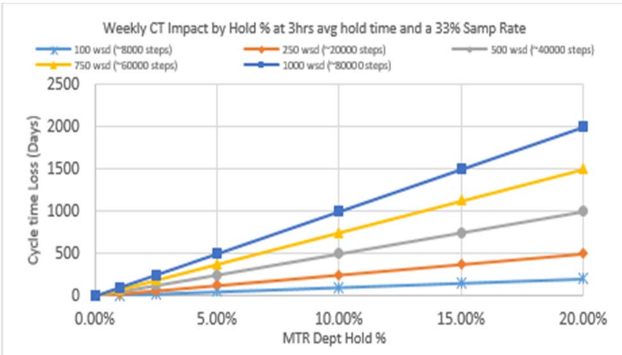


Fig. 1. Weekly Cycle Time impact due to Metrology Department lot holds.

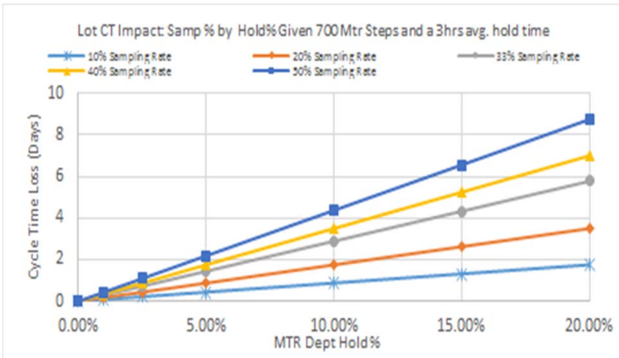


Fig. 2. Lot Cumulative Cycle Time assuming 700 metrology steps in route and 3h average hold time.

throughput, and other secondary resource ripples which compound the effect of lot holds even further. However, they do illustrate the significant impact lot holds have on a production line. For the metrology sector, a ten percent hold rate equates to one thousand days of cumulative cycle time lost per week, or approximately four days lost per lot from start to fab out.

By using structured problem solving to continually identify and eliminate the top detractors for lot holds the key performance indicator (hold %) improves, less resources are wasted and lots move faster. Additionally, further gains are achieved in throughput and cost as the secondary effects such as remeasurements and reworks reduce; wasting less tool time, process resources and materials. Human resources are also freed up to be more productive on other tasks. Sustaining this cycle of continuous improvement relies on consistent monitoring of the key metric to ensure actions taken reduce the hold frequency.

In this case to start the structured problem solving process, raw lot holds from multiple weeks were analyzed to understand if there was tool dependency, recipe dependency, product dependency or system dependency. At the same time, raw tool logs were filtered for recipe specific contributors and categorized. From the raw lot holds, we were able to understand the contributing factors. Based on this understanding, a strategy was put in place to enhance tool hardware, software, and recipe creation workflow to achieve reduction in lot holds percentage (Fig. 3). In phase 1, the focus was on boosting hardware performance while phase 2 was focused on software enhancements. Phase 3 and phase 4 were mainly focused on improving existing recipe BKM (best known method) and applying alternative recipe strategies. From Phase 1 to Phase 4, the target lot holds were reduced by a factor of 4.

| | Phase 1 | Phase 2 | Phase 3 | Phase 4 |
|---|---|---|---|---|
| Reduction of Contribution from Factor A (normalized) | 1 | 0.75 | 0.5 | 0.25 |
| Reduction of Contribution from Factor B (normalized) | 1 | 0.66 | 0.33 | 0.33 |
| Reduction of Contribution from Factor C (normalized) | 1 | 1 | 0.5 | 0.5 |
| Relative Target Lot Holds (normalized) | 1 | 0.75 | 0.5 | 0.25 |

Fig. 3. Improvement Strategy based on contributing factors from extensive data analysis. Phases 2, 3, and 4 are relative to Phase 1.

Based on the historical data analysis, the primary areas of opportunities were identified to be pattern recognition, hardware and software. Pattern recognition challenges were one of the contributors of lot holds. One of the root causes was found to be process induced pattern differences and contrast variation at different process steps (Fig. 4) (Fig. 5). Variability of incoming processes due to ongoing development work challenged our standard alignment strategies to become more robust. The use of an improved alignment strategy was implemented where alternate images were used for pattern recognition whenever primary images weren't recognized [5]. Once the alternate image was added to the recipe, the recipe would automatically use it when primary image failed. In addition, as part of Phase 3 we evaluated using an alternate feature for measurement site pattern recognition at each die, using a more optically stable feature close to the measurement pad – this methodology worked very well and there was significant improvement in lot holds. Fig. 6 shows the combined improvement in lot holds from some of the work done in Phases 1, 2, and 3. Subsequently

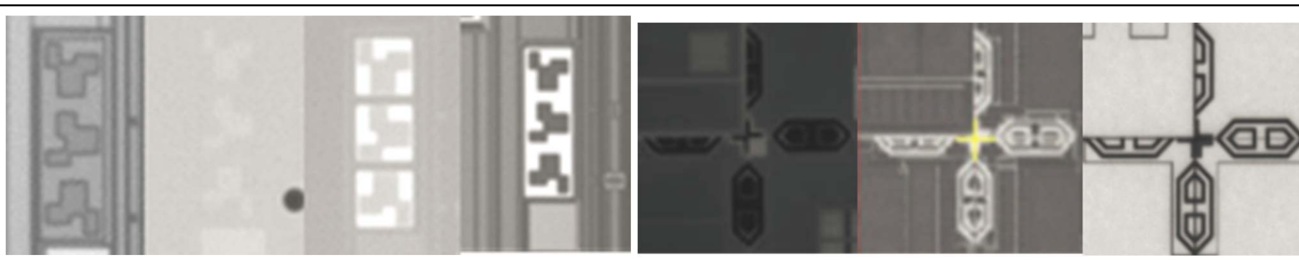

Fig. 4. Examples of die corner feature at different steps with pattern and contrast differences due to process variation.

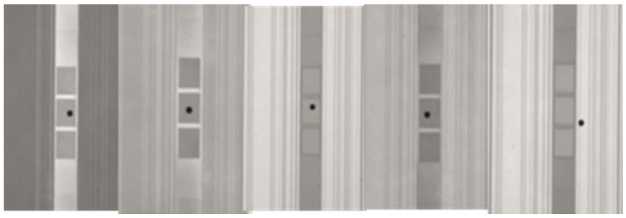

Fig. 5. Measurement site images at different process steps.

we were able to further improve on lot holds by implementing a new site positioning BKM.

New software was developed to support the new site positioning BKM. After migrating to the new BKM, measurement site discrepancies were eliminated. An additional monitor chart was set up to detect when there was any change in wafer positioning.

Some of the hardware related lot holds were found to be influenced by mechanical elasticity varying over time. To address this, the mechanical components were optimized and then monitored during future preventive maintenance procedures. Another area where significant improvements were achieved was in the hardware components involved in wafer transfer. Some scenarios that tested our recipe transfer capabilities also contributed to lot holds. We found that sticking with known locations like die size and measurement coordinates from specifications were more consistent in achieving high success.

When we first embarked on this project, lot holds related to software were difficult to identify. After much investigation, we were able to pinpoint the problem and software was developed to improve the system.

Throughout the lot holds improvement process, several key software features were fundamental enablers. The use of specialized image analysis software was one of the key enablers, allowing for image analysis improvement and algorithm enhancement, eliminating the need to hold wafers for recipe retraining. The wafer-less recipe creation software was very helpful as it worked independent of tool operating software, and allowed for faster tool recipes version comparison and troubleshooting. This software enabled several key features. A new methodology of creating recipes was developed which bypassed the need for keeping the wafers from new products on hold for recipe creation. Based on all the learnings, a new Best Known Methods (BKM) package was put together and several training sessions were held for all recipes creators.

A combination of specialized image analysis software, new recipe BKM, recipe training and enhanced alignment strategy was used to improve lot holds. Measurement site level lot holds were addressed by enabling improved site positioning BKM. Relevant engineers who worked on recipes were trained with a new recipe BKM that improved recipe robustness and portability. Moving away from training all features on tool, but rather employing the use of known feature locations were critical to the new recipe creation and modification methodology.

### B. *Recipe First-time Right*

For any new product started, there are invariably many metrology recipes that need to be created from scratch. To monitor the new product introduction process, the First-Time Right (FTR) method was developed as a key process indicator (KPI) which gauges four key elements of successful recipe introduction. The first condition checks if a recipe is prepared for use by the host. The second condition checks if a recipe is ready at the tool. The third condition checks recipe functionality at first pass. The final condition checks for recipe quality, which

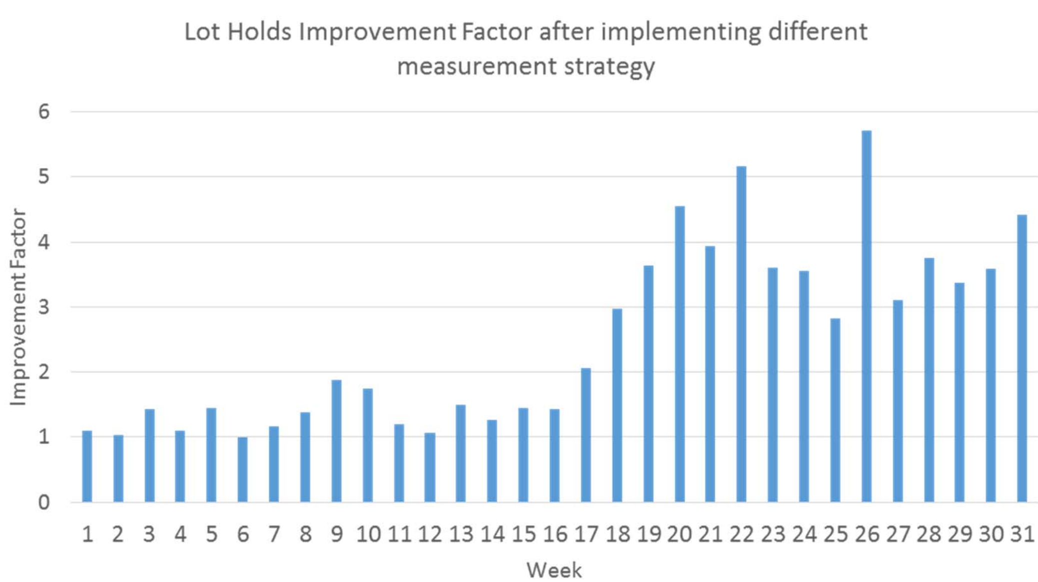


Fig. 6. Lot holds improvement factor over time after alternate measurement site strategy was implemented. The implementation was done over this time period at a non-uniform rate. Data represents a 31 week period and shows improvement in lot holds due to some of the work done in Phases 1, 2, 3 described in Fig 3.

can be impacted by process variation. Using the FTR KPI and its components, multiple aspects of recipe creation were quantized and sorted into critical categories to be addressed. [5]

In the past, a lead lot would be put on hold and the first recipe would be built with images taught from this lead lot. This adds to cycle time and success rates of subsequent steps copied from this first recipe were low. After refining the business process over several new product introductions, the final wafer-less recipe BKM was changed to only use known feature locations along with key representative feature images. To reduce the dependency on wafer taught images, new software features were developed to allow modified images. Initial tests with different feature types had mixed results as some features were changed significantly on the wafer after processing. After several rounds of evaluation, we were able to identify the features that were most successful when used to build wafer-less recipes. Close monitoring of the performance of these wafer-less recipes allowed us to further fine tune pattern recognition parameters to increase success rate and eliminate false positive scenarios. The use of internal reports allowed for new recipes to be easily tracked with estimated arrival time of lead lot, allowing for wafer-less recipe creation to be scheduled.

The same software features used in lot holds reduction were essential here as saved images could be analyzed and new pattern recognition parameters tested without the need for wafers. We also implemented our learnings from lot holds reduction in FTR BKM – enhanced alignment strategy, known feature locations and a new site positioning BKM. The waferless recipe creation software also allows for batch recipe creation which is very crucial in a foundry environment where there is a need for new recipes for every new product. Along with creating new recipes, it ensures that all recipes are made consistently and accurately and there is no errors introduced due to human involvement. The main components of the recipe specifically die size, lower left corner location, alignment feature location, measurement target location, sampling map etc. are generated by a fab software system and inserted in a file format that is compatible with the waferless recipe creation software. These files are then imported to the waferless recipe creation software and all the recipes relevant to a given product are created with a few clicks. Generating recipes in a batch methodology has reduced the engineering time involved by 10x compared to manually creating each recipe individually. Since all of the BKMs are consistently applied, other metrics like lot holds also see an improvement. This method also ensures that a new product will not have any missing recipes and there will be no loss to cycle time.

### *C. Fleet Availability and Matching*

Fleet availability is one way to measure the stability of fleet hardware and software in a high volume manufacturing fab. However, it is also one of the most difficult metrics to drive due to the number of possible root causes and hardware software interactions. To start, we took last several weeks tool downtime data and categorized the downtime into generic categories. This activity in itself took several iterations due to the massive amount of information involved. Based on this pareto (Fig. 7), an improvement plan was devised. The main categories that could be improved upon were found to be a combination of hardware, software and system components.

To boost long term performance, hardware CIP (continuous improvement program) was implemented, and additional quarterly maintenance checks were added. Software upgrades resolved majority of software related areas. In addition, we embarked on an in-depth baselining of each measurement tool, to address any systematic components that also led to tool downtime. This thorough health-check (Fig. 8) was performed to establish fleet baseline and determine the improvement plan. Each row represents a hardware parameter. A red cross indicates that hardware parameter for that tool was out of spec. A green check indicates that the hardware parameter for that tool was in spec. Fig.8 helps to visualize part of the methodology used to monitor and improve the fleet health.

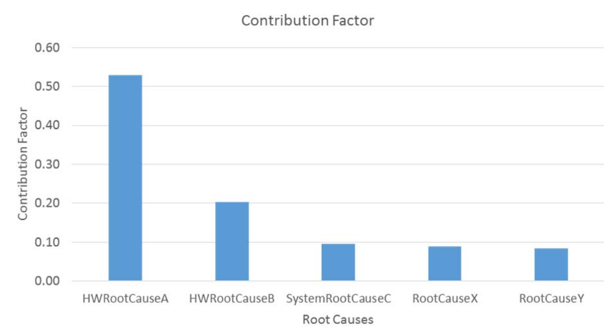


Fig. 7. Pareto of Top Downtime contributors.

| | Tool1 | Tool2 | Tool3 | Tool4 | Tool5 | Tool6 | ToolN-1 | ToolN |
|---|---|---|---|---|---|---|---|---|
| *Param 1* | ✗ | ✗ | ✓ | ✗ | ✗ | ✓ | ✓ | ✗ |
| *Param 2* | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| *Param 3* | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ | ✓ | ✓ |
| *Param 4* | ✗ | ✓ | ✓ | ✓ | ✓ | ✓ | ✗ | ✓ |
| *Param 5* | ✓ | ✓ | ✓ | ✗ | ✗ | ✓ | ✗ | ✗ |
| *Param 6* | ✗ | ✗ | ✗ | ✓ | ✓ | ✗ | ✓ | ✗ |

Fig. 8. Tool Overall Status after initial in-depth Health Check. Such a Health Check identifies where the hardware CIP improvements need to be focused.

The hardware CIP was a two-part process – improving upon existing optics alignment & HW parameter optimization to improve the baseline of the fleet. The improved calibration processes together with BKM for the preventive maintenance were key to maintain and sustain the fleet matching in manufacturing environment. Post CIP, monitoring was done on five different types of applications that include both film thickness and 3D profile measurements. Close tool monitoring also helped to identify possible issues and plan for scheduled work rather than unscheduled tool downtime. As tool activities influenced tool availability, it took some time for the tool availability trend to reflect the improvements. Fleet matching is another key metric used to monitor the measurement uncertainty and determines if the fleet meets the metrology budget for a given process step. As the fab transitioned to advanced processes, the metrology budget continued to tighten requiring improvement in fleet matching. The health check that helped to improve downtime also helped in tool to tool matching as repeatability was improved. Fig. 9 shows the improved sigma across tools for one of the parameters after Health Check, based on the same monitor wafer.

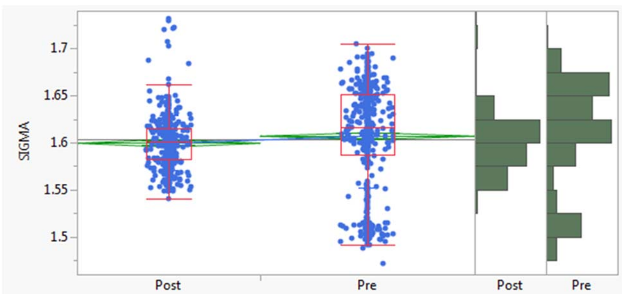


Fig. 9. Improvement in Variability across tools after Health Check

## III. TRACKING PROGRESS

All metrics were monitored weekly and contributing factors were continuously tracked to assess the progress of action plans. Metrics were automatically generated by host system to ensure consistent standard over time. Due to the influence of weekly activities, the metrics fluctuated week to week, so the 13 week average was used as a better indicator of progress. Over time, the action plans for lot holds and first-time right needed some adjustment due to changes in product technology and product mix. Based on tracking of these metrics and quick response to any uptick of lot holds, we were able to find the root cause and react quickly to address the change in production environment.

## IV. RESULTS

### A. *Lot Holds*

The percentage of lot holds for the Nova fleet improved significantly with stable and sustainable 13 week performance (Fig. 10).

### B. *First-Time Right*

With systematic analysis of how feature contrast was changing across process steps, we were able to find key representative images that were successful on majority of the process steps. After tool hardware were further improved during the lot holds improvement project, we found that new wafer-less recipes had a high rate of success. The improvement in First-Time Right metric demonstrates the sustainable success of wafer-less recipe creation strategy (Fig. 11).

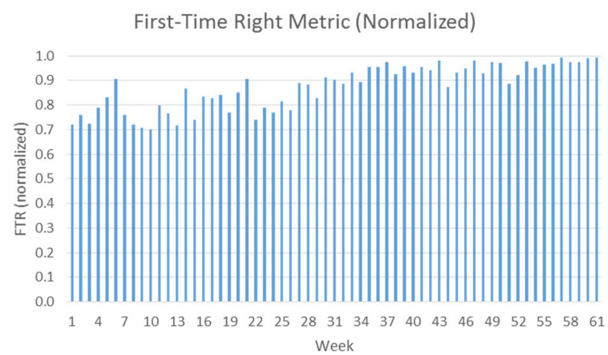


Fig. 11. First-Time Right Metric improvement factor over time.

### C. *Fleet Availability*

After baselining and preventive maintenance activities were implemented, fleet availability improved by more than 15% over 10 quarters time period (Fig. 12).

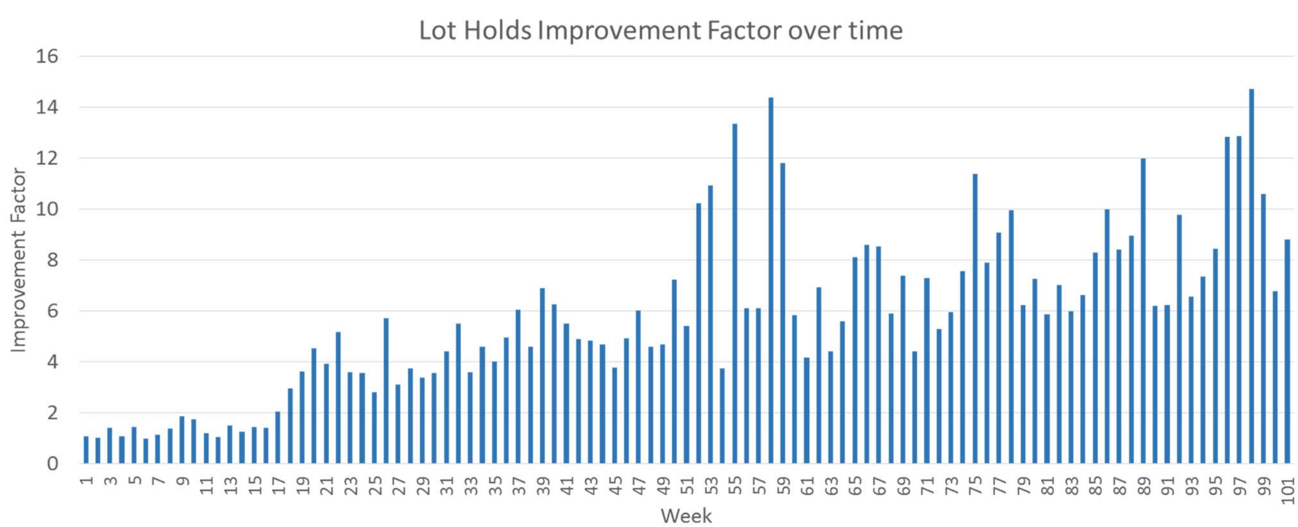


Fig. 10. Lot Holds Metric Improvement Factor over a 101 week period. This time period covers the work from all 4 Phases described in Fig 3.

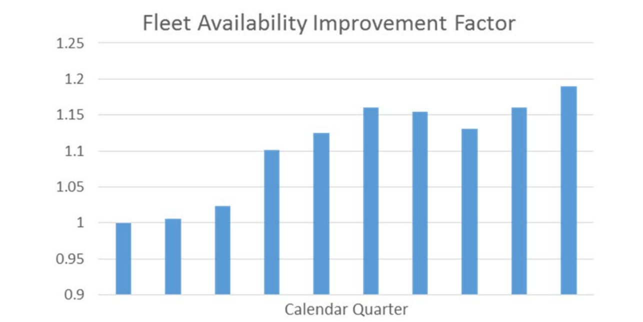

Fig. 12. Fleet Availability metric improvement.

### D. Fleet Matching

After the CIP was implemented, there is a noticeable improvement in fleet matching across the SPC monitoring parameters – ~35% on average (Fig. 13).

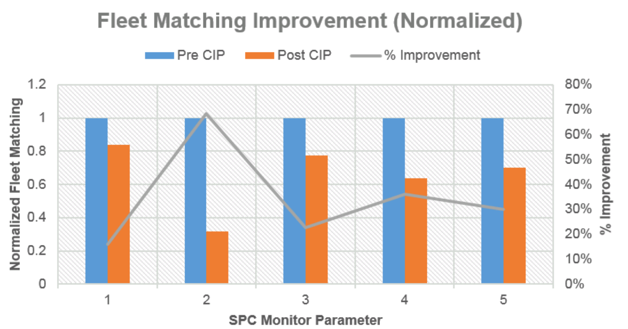

Fig. 13. Fleet Matching Metric improvement.

## V. SUMMARY AND CONCLUSIONS

In a foundry environment, cycle time and quality are critical operational metrics. The continuously increasing number of new product introductions (NPIs) and increasing role of automated process control (APC) in advanced technology nodes necessitates continuous improvement in quality cost and delivery metrics for metrology tools. In this work, the goals set for lot hold metric reduction and improvement in first time right, fleet availability and matching metrics required a refocusing of existing business processes and a mindset change among the key stakeholders. Through the structured problem solving process, regular tracking of these key performance metrics and strong teamwork, sustainable success was achieved and fleet capabilities established that were initially challenging.

The outcome of these fleet improvements was evident in improving lot cycle time from reduced avoidable lot hold waste and improved measurement quality from improved metrology tool matching. In particular, the enhanced recipe first time right performance was accompanied by the benefit of eliminating holds for new recipe creation on new product silicon, minimizing the metrology contribution to non-processing time of key new product inventory. In a volume manufacturing foundry, the total cycle time for leading lots is of critical importance to provide short cycles of learning to the end customer for any design iterations that may be required.

Other tangible benefits were observed in the reduction of engineering time that had previously been required to manage lot hold disposition, manual mode new product recipe creation, reduction of unscheduled downtime events associated with equipment availability, and managing recipe inhibits from tool differences. In particular, the new site positioning BKM in the metrology recipe significantly improved measurement success during the measurement recipe run sequence. Equally, sustained improvements in fleet availability were accompanied by improved preventive maintenance success and a more pro-active mindset to act on any tool deviations before exceeding equipment monitor control limits.

Regarding the tool matching improvement that was delivered in this work, in cases where inline measurements are used to drive automated process control schemes improved matching of the fleet attained during this work could potentially reduce the metrology noise component of the $C_p$ $C_{pk}$ process capability metrics, thus delivering improved quality of the end product in addition to the key cycle time benefits described previously.

In summary, the work presented here represents a holistic approach to improving and sustaining the key performance indices of a metrology fleet in a high volume production foundry and indicates the potential for initiation of similar improvement activities across other process and metrology tool families through the correct structured problem solving mindset and through strong collaborative environment between the equipment supplier and foundry teams.

## ACKNOWLEDGMENT

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