“Gantt Charts for Production Flow”: a Performance Analysis Framework for Shop Floor Control Effectiveness Evaluation and Monitoring

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Abstract

Shop floor controls have recently become fundamental for production controllers and industrial engineers, to apply scheduling and dispatching policies in the highly competitive semiconductor industry. Despite the emphasis put on Shop Floor Scheduling techniques, the impact on the actual operations of the fab may not reflect controllers’ expectations.

We have developed a framework which provides them with means of analyzing the production flow, through statistical analysis of equipment, operators and flow linearity parameters, and through data collection for historical comparisons between simulated and real activity of the fab, which can be helpful for evaluating and documenting the improvements on manufacturing performance offered by the use of shop floor controls.

1. Introduction

The semiconductor manufacturing cycle is one of the most difficult processes to model, with the purpose of analyzing the production flow and determining the best control policy that maximizes one or more performance objectives.

In the past few decades shop-floor scheduling has been recognized as an important tool in improving manufacturing performance, because simulating the activity of the fab through a complex mathematical model allows industrial engineers and production controllers to perform capacity, what-if analysis and planning and to offer important dispatching indications to people working on the shop floor [1].

A great deal of effort has been put on studying different shop floor controls, in order to measure the effectiveness of each scheduling policy, to compare the use of various dispatching rules or lot rankings [3] – [9], [17], [18]. The majority of this research has been concerned with theory development, applying and comparing scheduling dispatching techniques to a theoretical model and showing good results that confirmed the importance of shop floor controls.

But what about the practice of scheduling semiconductor wafer fabrication? In a real production environment, people have to cope with complex reality, with randomness in yields, reworks and resources unavailability, rapidly changing products and technologies, reentrant flows, time constrained operations, batching…

In R&D fabs the degree of uncertainty is even higher, because the processed wafers have low volumes but high variety; machine failures have greater impact due to not enough backups; engineering experiments lead to a higher number of inspections and reworks, consequently the production flow is less linear; finally, every new process to test and put in action suffers from a lack of historical data [10].

Therefore, it is important to have a means of analyzing performance parameters based on real data coming from the shop floor. For this purpose, the information system offered by MESs (Manufacturing Execution Systems) is fundamental to retrieve every kind of information which is related to the production process [2].

We have developed an analysis framework which, by collecting these data and performing statistical reprocessing of real values regarding fab equipments, operators and the whole production flow, offers industrial engineers and controllers the possibility to measure the impact of the shop floor scheduling policies on the real activity of the fab, comparing collected data with the results coming from a simulator of the manufacturing process [11].

2. Background

2.1. Literature Review

The theory developed for studying the effectiveness of production controls on fab activity is very huge and it would be too long to describe comprehensively all the approaches used to explore methods for productivity
improvement. Readers could find just a few examples in [3] - [9], [17], [18].

The research conducted in the last few years can be differentiated according to the performance measures to optimize (globally or locally), the control policies (scheduling and dispatching techniques) included in the model, the detail of the model used to reproduce the fab activity in a simulator.

Some authors claim that a reduction in mean cycle time is needed to optimize performance, others target reduction in cycle time variance in order to minimize lateness, thus respecting on time delivery. Critical Ratio Criterion also targets maximized on time delivery by prioritizing lots based on their current position, due date and remaining cycle time. Actually, due date satisfaction is a fundamental factor to increase competitiveness of a manufacturing enterprise.

Another important criterion is line balancing, i.e. targeting the linearity of product flow, in order to avoid bubbles of WIP (Work in Process, total number of wafers present in the manufacturing processing line) to form and to equilibrate workload in the different tools. Batch operation and random failures contribute to the formation of long queues in front of equipments, which leads to non-linearity in the production flow.

It is difficult to combine all these criteria, some of which are local rules while others are global, to optimize different performance objectives. To this purpose, dispatching and scheduling schemas involving a weighted average of various performance measures have been developed[5], [6].

Computer simulations are used to test the effectiveness of each policy. Once a decision is made regarding the release and control policy to adopt, the simulation, together with real-time information coming from MES [2], could be used to assign lot priorities in order to give people working on the shop floor dispatching indications on how to perform the lot transaction that contributes to the best performance in terms of local and global rules optimization.

The computer simulations are based on a model which resembles the real appearance of the fab. The model could be more or less detailed depending on the applications of the simulation. If we want to perform an extensive what-if analysis it is important to include in the model all the necessary details, possibly integrating uncertainty analysis [4], while for Simulation Based Real Time Scheduling [3] it is important to reduce the complexity of the model to minimize response times.

While researchers are still studying the effects of different control policies and industrial engineers and production controllers are trying to adopt sophisticated shop floor tools to improve production performance, the impact of these studies and control measures is not as big as expected, and it is not uncommon to discover that the real activity of the fab does not adhere to the dispatching decisions in a systematic way, due to lack of information in the model which should give the dispatching indications (hot lots non prioritized, setup number reduction not modeled…).

Therefore a tool for evaluating the real impact of shop floor controls on the activity of the fab is needed for industrial engineers and production controllers, which we will describe in section 3.1.

2.2. Case Study Overview

The motivation and data for this paper come from the work we have realized for an R&D fab of ST Microelectronics, which we plan to deploy also in a production fab.

It has the purpose of measuring manufacturing performance and to analyze the gap between real performance and the activity simulated by a mathematical simulator used in the previously mentioned fab, Brooks’ Autosched AP (Accelerated Processing) [11][15].

The simulator accepts inputs regarding fab status (WIP, equipments, products, operations…), processes all these information and creates a set of reports regarding lots and equipments status changes during the simulation horizon.

The inputs are coming though the MES system, which in our case study is Consilium Workstream [14]. Some information is extracted using COBOL extractions, querying Workstream database directly. Others come from a reporting system, Brooks APF (Advanced Productivity Family) reporter [15].

All the inputs are reprocessed through a set of procedures (called STAP toolbox) that adapt the format of the information extracted from Workstream and APF reporter to the input format needed by the simulator.

Finally, the outputs provided by the simulator are reprocessed by the STAP toolbox to build some reports for analysis or dispatching purposes.

The fab whose results we will present in this paper is a pilot line for technology development, which operates 24 hours per day, with work teams that change every 8 hours. An 8-hours period of work is called “shift”. The only exception is represented by Sunday night, when there is no regular personnel operating.

Three simulations per day are run, in order to produce a set of reports about fab activity in the following 8 hours shift. Everyday these data are collected to build an historical repository for reporting and performance analysis purpose.

3. Gantt charts for production flow

3.1. Scope, functionalities and applications

The tool we developed for Engineering Data Analysis focuses on the following performance measures:
Linearity and Global Process Flow

- **Moves per shift**: the number of moves performed in a shift (8-hours in our case) at a given operation (which is a step of one or more process flows), that indicates the number of transactions towards the next operation;
- **EOH (End of Hand) per shift**: the number of wafers that at the end of a given shift have finished one operation and are waiting for the next one or the wafers that are in process on equipment, constituting the work-in-process (WIP);
- **Cycle time**: Time taken by wafers in their passage from the entry to the exit of the plant, also called “manufacturing lead time”. This quantity is computed according to Little’s Law, which can be applied to every system in equilibrium in which customers arrive, spend time and depart. Assuming that \( \lambda \) is the average arrival rate, \( W \) the average time a customer spends in the system and \( L \) the average number of customers in the system, \( L \) can be computed using the formula:
  \[
  L = \frac{\lambda W}{1 - \frac{\lambda}{1 + \frac{\lambda}{P_t}} \left( \frac{C_a^2 + C_e^2}{2} \right)}
  \]
  which in terms of Cycle Time, WIP and throughput can be expressed as
  \[
  \text{cycle time} = \frac{WIP}{\text{Throughput}}
  \]

Equipment operation distributions and statistics

- **Equipment processing time, \( P_t \)**: the time spent by an equipment to perform a given operation, i.e. the period of time going from the logging of a new event for a quantity of wafers on the equipment until the processing end;
- **Number of wafers processed by an equipment**: the number of wafers which perform a given operation on one equipment;
- **Equipment Arrival rate, \( \lambda \)**: how many lots per hour arrive in front of one equipment;
- **Equipment MTBF (Mean Time Between Fails)**: The time range between two consecutive equipment fails (see figure 1);
- **Equipment MTTR (Mean Time To Repair)**: The time range needed to repair an equipment (see figure 2);
- **Equipment down percentage, \( \text{down\%} \)**: the time percentage an equipment spends in a down state (MTTR/MTBF);
- **Availability**: the time percentage an equipment is available for processing (Av=100-down\%);
- **Equipment cycle time multiplier**: the ratio between equipment cycle time and equipment effective processing time, the nearest to one the better the equipment performance [9][16]. The equipment cycle time is computed using the following approximation for a G/G/1 queuing system:
  \[
  \text{cycle time} = P_t^* \times \left( 1 + \frac{P_t^* \lambda}{1 + P_t^* \lambda} \left( \frac{C_a^2 + C_e^2}{2} \right) \right)
  \]
  where
  \[
  P_t^* = \frac{P_t}{Av}
  \]
  \( C_a \) is the coefficient of variation of lot arrival process \( C_v \) is the calculated system variation, given by
  \[
  C_v^2 = C_s^2 + (1 + C_r^2) \times RTR \times Av \times \text{down\%}
  \]
  \( C_r \) is the coefficient of variation of process time \( C_e \) is the coefficient of variation of MTTR
  \( RTR \) is repair time to service ratio, \( RTR=\text{MTTR}/P_r \).

Equipment operational reliability and efficiency

- **PTIME(%)**: percentage of time (in a 24-hours bucket, computed using the processing time coming from AP simulator) that the equipment should have theoretically spent to process a given quantity of wafers;
- **PET(Process Equipment Throughput)**: the time-weighted average (theoretical, computed using the processing time coming from AP simulator) of each single PRT (Process Recipe Throughput) for a given mix of recipes used, expressed in wafers/hour;
- **EP(Equipment Productivity)**: number of wafers/hour processed by the equipment;
- **EUR(%)(Equipment Utilization Rate)**: percentage of time (in a 24-hours bucket) the equipment spends in processing state;
- **OEE(%)(Overall Equipment Efficiency)**: equipment efficiency given by the ratio between EP and theoretical PET;
- **DOWN(%)**: percentage of time (in a 24-hours bucket) the equipment is not available to perform its intended function within its standard manufacturing specification (Scheduled maintenance operation, unscheduled failure repairing and qualification);
Charts for Production Flow” offers the following

• **Global and Local Production Flow**

  • **Moves per area**: moves per shift detailed by homogeneous areas (locations where equipments that perform similar process operations are grouped), compared to the theoretical moves performed by AP simulator and referred to the current *BOH* (*Beginning of Hand*, wafers ready to process or in process at the beginning of the shift) of the given area or the whole fab;
  
  • **Actual/theoretical moves correlation**: correlation between the real moves performed by the fab and the moves done with the same input conditions by the mathematical simulator Autosched AP;
  
  • **Moves per shift distribution**: parameters of the statistical distributions regarding the number of moves that the whole fab produces in one shift, considered in weekly or monthly buckets.

**Operators Team Performance**

• **Moves per team**: moves per shift detailed by homogeneous areas and by work team, averaged by weekly buckets;

• **Team turns**: correlation between the WIP and the Moves (Moves done by each team divided by the WIP quantity).

Focusing on the previously described factors, “Gantt Charts for Production Flow” offers the following capabilities:

• **ENG (%)**: percentage of time (in a 24-hours bucket) the equipment is operated to conduct engineering experiments. It includes process and equipment engineering (process characterization, equipment evaluation);

• **NO MAT (%)**: percentage of time (in a 24-hours bucket) the equipment is in condition to perform its required function, but some material useful for processing wafers is not available.

• **NO OP (%)**: percentage of time (in a 24-hours bucket) the equipment is in condition to perform its required function, but no operator or support functions available (including breaks, lunches and meetings);

• **NO WAF (%)**: percentage of time (in a 24-hours bucket) the equipment is in condition to perform its required function, but no wafers are available to be processed;

• **SETUP (%)**: percentage of time (in a 24-hours bucket) that include time for job preparation (change of recipe, mask, tooling, test program,....) between two regular production phases, time for production tests, process control, engineering runs associated to manufacturing lot, ...

• **Unknown time, UT (%)**: percentage of time (in a 24-hours bucket) spent by the equipment in a status which is not classifiable into the known inefficiencies stated above.

**Global and Local Production Flow**

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**Operators Team Performance**

• **Moves per team**: moves per shift detailed by homogeneous areas and by work team, averaged by weekly buckets;

• **Team turns**: correlation between the WIP and the Moves (Moves done by each team divided by the WIP quantity).

Focusing on the previously described factors, “Gantt Charts for Production Flow” offers the following capabilities:

• **visualize the global MOVES/EOH flow for a given technology/product/process group in a given date range, with a differently colored and shaded table which allows to detect immediately any non-linearity in the flow**;

• **visualize the fab cycle time (computed using Little's law) statistical distribution and parameters**;

• **analyze equipment performance, visualizing statistical distribution and parameters about equipment operation in a long time horizon (e.g. six months)**;

• **analyze data about equipment operational reliability and efficiency, referring to the best performance proposed by AP simulator, with a special attention to the unknown time, which has to be minimized**;

• **study the correlation between real and simulated fab activity, building a graph of the historical correlation of the couples (real, simulated) moves per shift**;

• **visualize moves distribution and related statistical parameters**;

• **visualize through a boxplot the distribution of fab moves in weekly shifts for a long fixed time horizon**;

• **analyze the progress of the gap between actual moves and AP simulated moves, detailed by shift and homogeneous areas, referred to the actual BOH**;

• **Analyze weekly/monthly turns team performance detailed by homogeneous areas**.

All the functionalities described above are really useful for production controllers and industrial engineers to monitor the performance of the fab.

The analysis of a process flow in terms of moves/EOH can help to detect some operations where the linearity is violated and it is possible to go deeply into the study of the problem, investigating the behavior of the equipment, operators and resources involved, to determine the root cause.

Non-linearity in the moves distribution could indicate a period of unavailability of some resource or the movement from batch equipment to a serial one, with the formation of queues in front of a station or station family which can also be encountered in the EOH distribution for the same time bucket.

An increasing number of EOH in certain areas of the process flow likely indicates a bottleneck station, meaning that parts are excessively stocked in front of some equipment.

Detecting anomalies in parts flow is very useful to indicate correction measures for reducing cycle times. This has several important consequences.

In R&D fabrication lines used for developing new products, reducing cycle time contributes to reduce designing and debugging products. Moreover, reducing
the time-to-market is very important in the current rapidly changing technological environment.

In production lines, reducing cycle-time improves the responsiveness to customers. Since, according to Little’s law, the mean number of wafers in the plant is proportional to their mean cycle-time, reducing the cycle time reduces the work-in-process and the capital invested on it.

This tool can also be used to detect variance in cycle-times, analyzing cycle time distribution. Reducing variances in cycle-times, caused by the randomness of arrivals and processing times, it is possible to predict safely when a wafer will complete production and exit the plant. This allows an improved ability to meet due-dates reliably.

Equipment statistics are useful to investigate the equipment operation along time, to build trends about equipment average parameters. In this way is possible to retrieve the equipment risk function, detecting if the performance of equipment is degrading or improving as time passes by.

The data collected concerning equipment activity factors can also be very useful for the fine tuning of the fab simulator, which could be automatically and periodically fed with the real collected data regarding processing time, MTBF, MTTR distribution types, average and standard deviation values. This would improve the management of the simulator, which is the core of the shop floor controls used in the fab, avoiding production controllers the tedious manual update of the simulator data.

The daily analysis of the data regarding equipments efficiency and unknown time is very important in the Capacity Improvement Program, which tends to reduce as much as possible for one equipment the periods of lack of operation due to inexplicable inefficiencies (unknown time), to improve equipment operational efficiency, to detect performance degradation and immediately take corrective actions.

Since the number of moves is one of the biggest significant factors in the fab’s performance, it is important to analyze related statistics and the comparison with the number of moves produced by the fab mathematical simulator. It is important to reduce as much as possible the gap with the simulated moves, and using the tool production controllers are able to monitor daily the gap reductions or enhancements, together with the correlation chart, studying the impact of different shop floor controls on the gap and the correlation and collecting the results of their analysis.

Finally, studying team weekly/monthly performance in terms of moves and turns detailed by homogeneous areas it is advisable to detect some recurrent inefficiency and to eventually link it to the team itself (e.g. need training, guiding lines…) or to the area, or to some logistics (e.g. transportation times from one bay to another).

The results obtained through Gantt Charts framework can be used for action planning and investments planning, collocating into the concept of continuous improvement, which is one of the most important guidelines of a production enterprise. These principles are best expressed and summarized by The Deming Cycle (PDCA, Plan \(\rightarrow\) Do \(\rightarrow\) Check \(\rightarrow\) Act), in figure 3.

![Figure 3. Deming cycle](image)

The cycle was proposed by W. Edwards Deming in the 1950's, meaning that business processes should be analyzed and measured to identify sources of variations that cause products to deviate from customer requirements. He recommended that business processes be placed in a continuous feedback loop so that managers can identify and change the parts of the process that need improvements. The steps of the cycle can be explained as follows:

**PLAN**: Design or revise business process components to improve results

**DO**: Implement the plan and measure its performance

**CHECK**: Assess the measurements and report the results to decision makers

**ACT**: Decide on changes needed to improve the process.

### 3.2. Results

In the following we will give some examples of the results we have obtained studying the pilot line fab with the characteristics described in section 2.2.

In figure 4 an example is given of the moves flow for a given technology for a period of one month. In the horizontal axis the succession of shifts (8-hours buckets) of the chosen time period is displayed, while in the vertical axis the steps characterizing the process flows of the technology are displayed, ordered from the first to the last step.
Figure 4. Technology moves flow

The cells of the flow are shaded with different colors (hue range [0,200]), according to the number of moves performed during a shift at one operation. The color legend is shown at the top of the picture, with higher hues (associated with lower moves per shift values) on the left and lower hues (associated with higher moves per shift values) on the right. Thus cells with low-hue color in the flow indicate a non-linearity in the process flow.

It is possible to visualize the production flow in detail, zooming in the image for some particular areas, like in figure 5, which represents the detail highlighted in figure 4. It is possible in this way to understand which operations of the process flow and time bucket are involved in the non-linearity.

Figure 5. Moves flow detail

Figure 6 presents an example of comparison between simulation and reality. It is referred to a period of about one month and a working area of a production fab. The red line represents the real moves trend, the blue line represents the simulated moves trend and the green bars represent the BOH of the working area. The data are detailed by shift (8-hours bucket). It is quite evident that the real fab activity tries to resemble the simulator’s dispatching indications, obtaining a very small gap, which becomes periodically higher, only during Sunday night’s closures.

Figure 6. Shift Gap Analysis

Figure 7 shows a particular type of chart, called boxplot, which is a compact graphical representation of the distribution of moves per shift, based on one year data collection. Generally, a box plot, also known as a box and whisker diagram, is a basic graphing tool that displays centering, spread, and distribution of a continuous data set, often used in exploratory data analysis.

Figure 7. Boxplot chart

In our case, along the horizontal axis the 21 8-hours shifts of the week are represented and for each shift the corresponding box contains the parameters of the dataset of the moves number related to that shift. For each dataset, the average value is represented by the blue dot in the box, the median is indicated by the black centre line, and the first and third quartiles are the edges of the pink area, which is known as the inter-quartile range (IQR). The extreme values (within 1.5 times the inter-quartile range from the upper or lower quartile) are the ends of the lines extending from the IQR, called “whiskers”. Points at a greater distance from the median than 1.5 times the IQR are plotted individually as asterisks. These points represent potential outliers.

With this chart it is possible to have in one shot a global vision of the moves done in a long time horizon in the same shift of the week, eventually detecting specific problems of that shift. In figure 7, for instance, it is
evident that the first shift of the week suffers from reorganization of the team after Sunday night break. The Sunday break is also evident in the last box of the boxplot, with a lower average, due to the fact that the regular personnel are not 100% present on Sunday night shift.

Figure 8 shows the moves per shift distribution for a period of six months, excluding the tails of the distribution, due to closures, strikes or failures. The result is a Gaussian distribution, centered on the average number of moves done by the whole fab in one 8-hours shift.

![Figure 8. Moves per shift distribution](image)

Together with the distribution, a set of statistical parameters representing the distribution characteristics is displayed. An example is in table 1, which refers to the distribution of figure 8.

<table>
<thead>
<tr>
<th>Number of data</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average range</td>
<td>3000.29</td>
</tr>
<tr>
<td>Average deviation</td>
<td>624.547</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>786.152</td>
</tr>
<tr>
<td>Variance</td>
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</tr>
<tr>
<td>Skewness</td>
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</tr>
<tr>
<td>Kurtosis</td>
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<tr>
<td>Median value</td>
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</tr>
<tr>
<td>Coefficient of variation</td>
<td>0.262026</td>
</tr>
</tbody>
</table>

Table 1. Statistical parameters

Similar graphs and reports are produced by the tool for analyzing all the equipment performance parameters.

3.3. Conclusions

In order to measure the emphasis put on shop floor scheduling by the operation personnel of a semiconductor fabrication facility, we have developed an analysis framework which allows production controls and industrial engineers to track factory activity and progress, through a set of graphs, reports and tables which focus on different performance measures.

It has the purpose of providing them with a global vision of the fab from various points of view, which can be combined for an efficient analysis and immediate problem detection.

“Gantt Charts for production flow” framework has been used in an ST R&D fab, whose personnel has received a training session and has expressed a good feedback on the usefulness of it for their daily performance analysis.

The tool is going to be deployed in a production fab, which would be helpful to have a feedback from a real production fab.

3.4. Acknowledgment

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3.5. References


