Closed-Loop Measurement of Equipment Efficiency and Equipment Capacity

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Introduction

Important concept from "TPM" paradigm:

*Overall Equipment Efficiency (OEE)*

Rigorously account for all losses of machine efficiency

- quantify all opportunities to improve throughput

Useful potential by-product:

Rigorous maintenance of data required for production planning and scheduling
Introduction (cont.)

The evolution in many US companies:

Quality control and six-sigma campaign (process control, statistical analysis)

Cycle time reduction campaign

TPM campaign – sometimes tried and aborted

While die yields and cycle times have been improved, equipment productivity is still low
Sources of Cost Reduction - until 1980s

- Feature size
- Wafer size
- Yield improvement
- Other - equipment throughput, etc.

25-30% per year cost reduction to consumer

Log $ per function (bit or transistor)

12%
8%
5%
3%

Time

1980s
Sources of Cost Reduction – 1990s

25-30% per year cost reduction to consumer

Feature size
Wafer size
Yield improvement
Other - equipment throughput, etc.

Log $ per function

12-14%
4%
2%
7-10%

Time
1998

Equipment Efficiency and Capacity
Sources of Cost Reduction – After 1998

Feature size: 12-14%
Wafer size: 4%
Yield: 2%
Equipment: 7-10%

Would have to be above 10% per year!

25-30% per year cost reduction to consumer

Log $ per function

Time

1998

Equipment Efficiency and Capacity
The state of current practice in many companies:

Factories measure "equipment availability," e.g., 78%

Factories measure "equipment utilization," e.g., 53%

**Capacity is** thought to be "somewhere in between"

True overall efficiency of machines is not measured

Machine rates ("UPHs") or standard times (ST) are re-evaluated periodically, sometimes measured only as averages across different operations.
Why measure equipment efficiency?

• For those who do measure it, OEE of semiconductor processing equipment is revealed to be on the order of 30 - 75 percent. A big opportunity!

• Data developed for measurement of equipment efficiency is valuable for factory capacity analysis.
Introduction (cont.)

Goals:

– Practical strategy for OEE data collection and analysis
– Theoretical processing time formulas for common equipment types
– Common data base and methodology supporting both equipment improvement and capacity analysis
Outline of this talk

• Definition of **overall equipment efficiency**
• Example processing time models
• **Closed-loop measurement** technique
• Formal definition of **equipment capacity**
• Data collection techniques
• Final remarks
What is equipment efficiency?

Overall equipment efficiency is the percentage of total time in an observation period that an equipment asset was utilized to generate salable output according to theoretical or ideal machine rates.

\[
OEE = \frac{S}{T} , \quad \text{where } S = \text{“should-take” time to process useful output actually completed, } T = \text{total elapsed time.}
\]
The sources of efficiency loss

Non-productive time:

Equipment Down Time (DT):
- Unplanned down time (failures, wait for repairs & repairs)
- Planned down time (preventive maintenance, engineering)

Equipment Idle Time (IT):
- No WIP
- No operator
- No materials
The sources of efficiency loss (cont.)

Demand efficiency (DE)

• Demand inefficiency = time spent processing items not in demand

• Hereafter, we shall assume DE = 100%
The sources of efficiency loss (cont.)

Losses occurring during production:

• **Quality loss** - time spent processing items scrapped or reworked

• **Speed Loss** - actual production time in excess of theoretically required time complete processing
Metrics for measuring efficiency

• Assume \( DT \) and \( IT \) are expressed as fractions of the total elapsed time. Then we define

• Availability = 1.0 - \( DT \)

• Fraction Productive Time (or Utilization of total time) \( PT = 1.0 - DT - IT \)

• Utilization of available time = \( PT / AT = PT / (1.0 - DT) \)
Metrics for efficiency (cont.)

- **Rate efficiency (RE)** - theoretical time to process all items actually run divided by actual production time

- **RE** = \[ \sum ( \text{Total units completed through each process step} ) \times ( \text{Theoretical processing time for the step} ) \] / ( \text{Total actual (recorded) production time} )

- In a fab bay with ten “identical” machines, the actual machine speeds often vary by 20%. Carefully computing rate efficiency reveals these losses.
• **Quality efficiency (QE)** – theoretical time to process the items completed with good quality divided by theoretical time to process all items run

• \[ QE = \left[ \sum \left( \text{Total good units completed through each process step} \right) \times \left( \text{Theoretical processing time for the step} \right) \right] / \left[ \sum \left( \text{Total units completed through each process step} \right) \times \left( \text{Theoretical processing time for the step} \right) \right] \]
Formal Definition of Overall Equipment Efficiency

\[ OEE = (1.0 - DT - IT)(RE)(QE) = (PT)(RE)(QE) = \frac{S}{T} \]

Overall efficiency is “earned utilization,” i.e., the reported productive time reduced by the various factors accounting for speed and quality losses during productive time.
OEE Definition (cont.)

• Note that the accuracy of the OEE figure is solely dependent on the accuracy of:
  – theoretical process times for each recipe
  – quantity of each recipe processed and the quantity with good quality

• The accuracy of the OEE figure is independent of the accuracy of tracking down times and idle times
OEE Definition (cont.)

- Expansion of OEE into its component terms quantifies the amount of efficiency loss of each type:

  \[ OEE = (AT) \frac{(PT)}{AT} \cdot (RE) \cdot (QE) \]


- Note: Later in the course, I will sometimes write \( A \) instead of \( AT \), \( U \) instead of \( PT \), and \( U / A \) instead of \( PT / AT \)
Rate Efficiency

To measure Rate Efficiency and Quality Efficiency (and hence OEE), we need **Theoretical Processing Times (TPT)**, defined for each process step, based on:

- **Process specification (“process spec”)** for each process step
- **Theoretical time per wafer** as a function of process spec
Examples of Processing Times

Photolithography Projection Aligner

Process Specs indicate exposure setting to use, whether to manual or auto align, and if test wafer is required.

Theoretical times to be established:

- exposure time as a function of exposure setting,
- mechanical time to insert wafer and align and time to flush last wafer of lot, and
- time for operator to exchange lots.
What is “theoretical” depends on one’s assumptions.

When computing OEE score for the photo engineer, the extra time required to manually align, time to insert new reticle and time to run test wafer are considered waste that potentially can be engineered out.

\[
\text{TPT} = (\text{insert \\& align time}) + (\text{exposure time}) + \{ (\text{flush last wafer time}) + (\text{lot exchange time}) \} / (\text{full lot size})
\]
Another Example - Canon 5X Stepper

Process specification indicates **exposure energy (EE)** and whether or not sample wafer is required

**Machine parameters:** time to exchange wafers on X-Y Stage \((XT)\), initial align time \((AT)\), move time \((MT)\), blade time \((BT)\), lamp intensity \((LI)\)

**Product parameters:** number of exposures \((NE)\), whether or not blading is required \((B=1 \text{ if so, } B=0 \text{ if not})\)

\[
TPT = XT + AT + NE \times (EE/LI) + (NE-2) \times MT + \text{Max} (B \times BT, MT)
\]
## Canon 5X Stepper (cont.)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Theoretical</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time (sec)</td>
<td>Time (sec)</td>
</tr>
<tr>
<td>XT</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>AT</td>
<td>27</td>
<td>29</td>
</tr>
<tr>
<td>MT</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>BT</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>LI</td>
<td>770mW/sq cm</td>
<td>720mW/sq cm</td>
</tr>
</tbody>
</table>
Additional parameters:

- Time to load recipe (30 sec, can be done in parallel; reticle loading always done in parallel)
- Time to cycle first wafer in to X-Y stage (80 sec)
- Time to cycle last wafer out of X-Y stage (37 sec)
- Wait time to develop and inspect sample wafer

None of these parameters are part of theoretical time.
Another Example - Varian High Current Ion Implanter

Process specification indicates species, dose, energy

Cross-reference table relates species, dose and energy to target implant beam current

Machine parameters: vent and lower time (VT), robot exchange wafers time (XT), lift and pump-down time (PT), wheel rev-up time (RT), end station load size (LS)

Operator parameter: time to enter recipe and shift and tune beam (BSU)
## High Current Ion Implanter (cont.)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Theoretical Time (sec)</th>
<th>Average Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSU</td>
<td>56</td>
<td>115</td>
</tr>
<tr>
<td>RT</td>
<td>34</td>
<td>69</td>
</tr>
<tr>
<td>XT</td>
<td>127</td>
<td>131</td>
</tr>
<tr>
<td>VT</td>
<td>37</td>
<td>46</td>
</tr>
<tr>
<td>PT</td>
<td>77</td>
<td>79</td>
</tr>
</tbody>
</table>
High Current Ion Implanter (cont.)

Theoretical Implant time:

\[ IT = \frac{(1.602 \times 10^{-19}) \times (\text{Dose}) \times (\text{Area})}{(\text{Current})} \]

Actual beam current often is below target beam current - a major loss of rate efficiency.

Theoretical Time Per Wafer:

\[ TPT = \frac{\{ \text{BSU} + \text{Max} [ \text{VT} + \text{XT} + \text{PT}, \text{RT} + \text{IT} ] \}}{\text{LS}} \]
Etch, CVD or Metal Cluster Tools

- Define theoretical process time for each chamber recipe (robot load, pump, process, vent, robot unload)
- Track which recipes were run in which chambers and compute OEE for each chamber
- View cluster tool as a bank of parallel “machines” (each chamber is viewed as a machine)
- Compute OEE for the “bank” of chambers:

Cluster tool OEE = Avg. of chamber OEE scores
Example Rate Efficiency Losses

5X Steppers - low lamp intensity, reticle and lot exchange time, wait for sample wafer results

Implant - low beam current, load/unload delay

1X Steppers - low power supply, mechanical align time, reticle and lot change time

Etchers - excessive vent time, excessive etch time

CVD - excessive clean cycles

Etch Cluster Tool - inefficient robot logic, load delay
Closed Loop Measurement

Suppose **some down time or idle time is unreported.**

Then **production time would be overstated.**

But then **rate efficiency would be understated** by the same factor. $RE = \left( \frac{\text{Should-take time}}{\text{Production time}} \right)$

The **OEE score would remain the same:**

$OEE = \left( \frac{\text{Production time}}{\text{Total time}} \right) \cdot (QE) \cdot (RE)$

The measurement scheme is thus **closed-loop.**
Open Loop Measurement

Many semiconductor companies have tried to use equipment utilization as a metric to monitor performance, often with disappointing results.

Example: Company A set up procedures for reporting into top management the utilization of key equipment. Data from factories showed utilization going up, but output staying flat! Finally, top management said, "Just report total wafers processed per machine."
Open Loop (cont.)

Analysis: Company A discovered that the utilization metric is unreliable: If some non-production time goes unreported, there is no feedback mechanism to correct it!

• The average machine speed is a better metric, but not as good as OEE since it is confounded by differences in product mix.
Closed Loop Measurement

Conclusion: Precise measurement of equipment efficiency requires a data base of the true Theoretical Processing Times.

The OEE score does not depend on the precision of measurement of down time and idle time.

(But of course, stratifying the overall losses by source is helpful.)
OEE vs. Capacity Analysis

OEE is a measurement of past performance. But production planning uses predictions of future efficiencies.

An actual value for each component of efficiency loss is computed over review periods such as weeks ("Actual_DT", “Actual_RE”, etc.)

A standard for each component is forecast, perhaps based on moving averages of the actuals ("Std_DT", “Std_RE”, etc.)
Consider the usual capacity constraints in a production planning model:

\[ \sum_{i} a_{ji} x_{it} \leq c_{jt} \]

The variables \( x_{it} \) define the planned starts of product \( i \) in period \( t \). \( a_{ji} \) denotes the process time for product \( i \) on equipment \( j \) and \( c_{jt} \) denotes the capacity of equipment \( j \) in period \( t \).

Exactly how are the parameters \( a_{ji} \) and \( c_{jt} \) defined?
Capacity Analysis (cont.)

\[
\sum_{i} a_{ji} x_{it} \leq c_{jt}
\]

If all efficiency losses were independent of production plan (i.e., independent of the \(x_{it}\)'s), we could use the OEE score to define the right-hand side parameter \(c_{jt}\) and we could use the theoretical processing times to define the left-hand side parameters \(a_{ji}\).
Capacity Analysis (cont.)

\[ \sum_{i} a_{ji} x_{it} \leq c_{jt} \]

Unfortunately, OEE depends on the production plan:

- A portion of total idle time is **planned idle time**, based on the scheduled workload and the equipment set.

- Losses for **machine setups, partial machine loads, rework and scrap** may vary by product and so may depend on the product mix.
Effective Processing Times

For capacity analysis, we should use effective processing times EPT that account for losses due to setups, partial load sizes and rework.

Recall photolithography projection aligner

\[
EPT = \{ (\text{insert} \& \text{align}) + (\text{manual align}) + (\text{exposure}) \\
+ [ (\text{flush last wafer}) + (\text{exchange cassettes}) ] / [ (\text{line yield}) \times (\text{starting lot size}) ] \\
+ [ (\text{reticle change} + \text{test wafer}) ] / [ (\text{avg. batch size}) ] \} \\
\{ 1.0 + \text{avg. rework factor} \}
\]
Capacity Rate Efficiency

Using the effective processing times, we define

**Capacity Rate Efficiency:**

\[
CRE = \left[ \sum \left( \text{Total units completed through each process step} \right) \times \left( \text{EPT for the step} \right) \right] / \left( \text{Total reported production time} \right)
\]
Minimum IT - Maximum U

For the purposes of defining capacity we need to establish the **minimum idle time MIT**, or, equivalently, the **maximum utilization U** for each equipment type.

As will be discussed later, the maximum allowed utilization U determines the cycle times for process steps performed by the equipment.

We assume that **max U** (equivalently, MIT) is **pre-specified for each equipment type**.
Minimum Idle Time vs. Cycle Time

MIT depends on allowed cycle time (i.e., on allowed WIP level) as well as on variability.

Minimum Idle Time MIT (case of high variability)

Equipment Efficiency and Capacity
Formal Definition of Capacity

We define an equipment efficiency metric suitable for capacity analysis, which we term **Capacity** Equipment Efficiency (CEE):

\[ CEE = (1.0 - DT - MIT) \times (CRE) = (\text{Max } U) \times (CRE) \]
Formal Definition of Capacity (cont.)

Equipment Capacity = (CEE) \times (Quantity In Service) \times \text{(Hours Worked Per Working Day)}.

**Equipment Capacity** is expressed in machine hours per working day. It expresses the maximum number of machine hours per day that can be devoted to processing activity.
Capacity analysis

\[ \sum_{i} a_{ji}x_{it} \leq c_{jt} \]

The right hand side parameter is the equipment capacity in the planning period multiplied by the number of working days in the period.

The left-hand side parameter for a process step appearing in a capacity constraint is the EPT (multiplied by the line yield up to the process step if \( x \) measures process starts).
Data Collection Strategies

Low - Tech

- **Paper logs** for WIP and equipment tracking.
- Logs are key-punched into data base off-line.

Low - Tech

- **CAM system** for manual WIP and equipment tracking.
**FIGURE 2**
Form for Equipment Tracking Used In Device Testing
*(Courtesy of Harris Corporation)*

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**Equipment Efficiency and Capacity**
# Equipment Efficiency and Capacity

**FIGURE 3**
Form for Equipment Tracking Used In Wafer Fabrication
(Courtesy of NEC Electronics, Inc.)
Hi - Tech (automated data capture)

• Upload data from machine event logs, or capture logging of machine events via “SECS II” interface

Under either low-tech or high-tech strategies, a database maintaining the TPT and EPT processing times for each spec is required.
Final Remarks: Automated OEE

• Periodic time-study analysis should be replaced by (1) formulas to compute theoretical processing times as a function of the process specs plus (2) computerized measurement of efficiency losses.

• Capacity and efficiency figures should be continuously maintained by automated systems, not just periodically updated by manual IE studies.