SEMI E124-0703
PROVISIONAL GUIDE FOR DEFINITION AND CALCULATION OF OVERALL FACTORY EFFICIENCY (OFE) AND OTHER ASSOCIATED FACTORY-LEVEL PRODUCTIVITY METRICS

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1 Purpose

1.1 This Guide describes metrics that show how well a factory is operating compared to how well it could be operating (for the given product mix). These metrics can be used for tracking factory performance (in value-added production) in a way that rewards good operational decisions and that is not easy to adversely manipulate. They can be used in a process of ongoing improvement that can be visible to all levels of a semiconductor manufacturing organization.

1.2 The metrics in this Guide are intended for evaluating the relative efficiency of factory production after the factory is in production, not for capacity analysis while the factory is being designed or redesigned. However, some of these metrics can be used in factory simulations for choosing equipment sets and scheduling policies.

2 Scope

2.1 To evaluate the overall effectiveness of a factory, there are at least three things in need of measurement: production, utilization of assets, and costs. This Guide focuses on evaluating production; utilization of assets and costs (as well as other economic factors) are outside its scope. See § R3-1.1 in Related Information 3 for a discussion of metrics in other areas.

2.2 This Guide describes metrics for an entire integrated production line. Multiple production lines in the same factory may be evaluated separately if they do not share resources (such as material handling or production equipment).

2.3 This Guide is provisional because *overall factory efficiency* (*OFE*) is a new concept. Once the metrics have been validated by collecting data in production factories, computing the metrics, and evaluating their sensitivity to the data, this Guide should be modified and upgraded from provisional status (as specified in the SEMI regulations). Also, additional supplemental metrics may be defined, and the metric definitions given here may be expanded to truly comprehend assembly operations.

NOTICE: SEMI Standards and Safety Guidelines do not purport to address all safety issues associated with their use. It is the responsibility of the users of the Documents to establish appropriate safety and health practices, and determine the applicability of regulatory or other limitations prior to use.

3 Limitations

3.1 In the context of this Guide, it is important to note that factory-level productivity is impacted greatly by factors beyond the factory itself, including material availability, device designs, and customer demand.

3.2 The metrics in this Guide are intended for evaluating the overall efficiency of factory production, not for diagnosing problems (or opportunities for improvement) in the factory, although some component metrics can be used that way. See § R3-1.2 in Related Information 3 for a discussion of the differences between the two kinds of metrics.

3.3 This Guide provides metrics and calculations for measuring the overall productivity only of manufacturing environments (such as wafer fabs, flat panel factories, and some disk-drive production facilities) in which product substrates move through the factory with no assembly or disassembly processes. These metrics can be applied in a post-wafer back-end chip production facility if the lead frames are considered to be consumable materials (not units of production in their own right). However, in the future this Guide may be extended to comprehend other, more complex manufacturing environments (including assembly operations).

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4 Referenced Standards

4.1 *SEMI Standards*

SEMI E10 — Specification for Definition and Measurement of Equipment Reliability, Availability, and Maintainability (RAM)

SEMI E79 — Standard for Definition and Measurement of Equipment Productivity

NOTICE: Unless otherwise indicated, all documents cited shall be the latest published versions.

5 Terminology

NOTE 1: All of the metrics defined below should be calculated with respect to the period being measured.

5.1 *Definitions*

5.1.1 *actual throughput rate* — the finished units out divided by the total time (shows how fast finished wafers flow out of the factory). See Equation 19.

5.1.2 *availability efficiency (time divided by time)* — the fraction of total time that the equipment is in a condition to perform its intended function (SEMI E79).

5.1.3 *average cycle time* — the (unweighted) average of cycle time over all of the units of production in finished units out.

5.1.4 *average work in process (WIP)* — the average cycle time multiplied by the actual throughput rate (shows how many eventually finished units of production fill the "pipeline" on average). See Equation 15.

NOTE 2: This metric is not an average of the *WIP* over time, since that would include units that are later scrapped before finishing.

5.1.5 *balance efficiency* — the *critical WIP* divided by the *process capacity* (measures how well the equipment sets are balanced). See Equation 5.

5.1.6 *best-case cycle time* — the larger of the *theoretical cycle time* and the quotient of the *average WIP* divided by the *bottleneck throughput rate* (shows the best cycle time that the factory can do given the WIP loading). See Equation 18.

5.1.7 *best-case throughput rate* — the smaller of the *bottleneck throughput rate* and the quotient of the *average WIP* divided by the *theoretical cycle time* (shows the best throughput rate that the factory can do given the WIP loading). See Equation 20.

5.1.8 *bottleneck throughput rate* (R_{max}) — the upper bound on the factory throughput rate imposed by the current bottleneck equipment set. If a process change for a product causes this metric to change, it should be considered a different product for the purposes of performing these computations. See Equation 17.

NOTE 3: This metric is similar to (but not the same as) the *theoretical unit throughput by recipe* metric (see ¶ 5.1.32) from SEMI E79.

NOTE 4: This metric is not an average over the bottleneck throughput rates of each product.

5.1.9 *critical WIP* (W_0) — the *theoretical cycle time* multiplied by the *bottleneck throughput rate* (gives the WIP level that theoretically allows the factory to have the highest throughput rate with the shortest cycle time). See Equation 10.

5.1.10 *cycle time* — the amount of time a unit of production spends as WIP in the factory.

5.1.11 *finished units out* — the number of units of production that finish processing and testing during the period being measured.

5.1.12 *good unit equivalents (GUE) out* — the (possibly non-integer) number of units of production required to contain all of the good product that exits the factory during the period being measured. See Equation 12.

5.1.13 *line yield* — the fraction of units leaving the factory that have finished processing (measures relative material losses such as scrapped units). See Equation 6.

5.1.14 *normalized production efficiency* — the *production efficiency* to the power of the *normalizing exponent* (measures the normalized efficiency of the process with respect to factory dynamics). See Equation 4.

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5.1.15 *normalizing exponent* — power that normalizes the *production efficiency* so that a value of ½ for *normalized production efficiency* indicates that the factory is performing at the level of the threshold case (which divides a well-run factory from one badly operated). See Equation 9. See §§ R1-1.7 and R1-1.8 in Related Information 1 for a discussion of the meaning of the threshold case and a derivation of mathematical expression for the *normalizing exponent*.

5.1.16 *operational efficiency (time divided by time)* — the fraction of equipment *uptime* that the equipment is processing actual units. [SEMI E79]

5.1.17 *overall equipment efficiency (OEE) (time divided by time)* — a metric of equipment performance, expressing the theoretical production time for the effective unit output divided by the *total time*. [SEMI E79]

5.1.18 *overall factory efficiency (OFE)* — the *volume efficiency* multiplied by the *yield efficiency* (shows how well a factory is operating compared to how well it could be operating for the given product mix). See Equation 1.

5.1.19 *process capacity* — the maximum number of *units of production* that can be processed simultaneously throughout the factory (including units being transported by material handling vehicles). See Equation 11.

5.1.20 *production efficiency* — the *throughput-rate and cycle-time efficiency* multiplied by the *WIP efficiency* (measures the efficiency of production with respect to factory dynamics). See Equation 8.

5.1.21 *quality efficiency (time divided by time)* — the theoretical production time for effective units divided by the theoretical production time for actual units. [SEMI E79]

5.1.22 *scrapped units out* — the number of units of production (including broken units, external rework, etc.) that exit the factory without finishing production during the period being measured.

5.1.23 *set of bottleneck equipment* (F_{e^*}) — the collection of production equipment of the same type that has the highest average *operational efficiency* in the factory during the period being measured. Elements of this set are indicated by "*f*", and the equipment type is indicated by "*e**".

NOTE 5: This set of bottleneck equipment might not be the equipment set (often the expensive lithography exposure equipment) that was planned to be the bottleneck in the factory, but rather the equipment set with the highest average *operational efficiency* (the fraction of time in use when available) during the period being measured. If another equipment set experiences significantly lower availability than expected, it might become the bottleneck. Thus, the sets of bottleneck equipment may be different between two adjacent time periods, and the set of bottleneck equipment for the period combining the two adjacent periods may be different from the other two sets.

5.1.24 *set of equipment of type e* (F_e) — the collection of production equipment of type $e \in E$ in the factory. Elements of this set are indicated by "*f*".

5.1.25 *set of equipment types* (E) — the collection of the different types of production equipment in the factory, including metrology equipment and material handling vehicles and conveyors. Elements of this set (which are the different types of equipment) are indicated by "*e*".

NOTE 6: If units are transported manually between process steps, then the human transporters (and any carts or mechanized vehicles that they operate to perform the movement) should be considered a type of equipment for the purpose of computing the metrics in this Guide. This is not intended to dehumanize people, but to ensure that the manual transport time is included in such metrics as *theoretical cycle time*.

5.1.26 *set of process steps of product type p on equipment type e* (S_{pe}) — the collection of the different process steps (including metrology inspection and material handling transport) planned for a unit of production of product type *p* on equipment of type *e* in the factory. Elements of this set are indicated by "*s*".

5.1.27 *set of product types (P)* — the collection of the different types of products manufactured in the factory. Elements of this set are indicated by "*p*".

5.1.28 *test yield* — the fraction of units leaving the factory that have finished processing and have passed final testing (measures relative losses due to parametric or functional failure). See Equation 7.

5.1.29 *theoretical cycle time* (T_{min}) — the minimum time required to process a unit of production through the factory (including material handling transport time) if the unit never has to wait for equipment or a vehicle to become available and if sequence-dependent set-ups never have to be performed. This is also known as the raw process time. If a process change for a product causes this metric to change, it should be considered a different product for the purposes of

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performing these computations. If more than one product (or process flow) is represented in the output, an average is taken over each of the products' *theoretical cycle time* weighted by the fraction of that product found in *finished units out*. See Equation 16.

NOTE 7: This metric is similar to (but not the same as) the *theoretical production time per unit* (*THT*) metric (see ¶ 5.1.30) used in SEMI E79 from CSM 21 and 42[1].

5.1.30 *theoretical production time per unit* (*THT*) *(time per unit)* — for a given production recipe performed by a given processing module, the minimum time to complete processing on one unit of production assuming no efficiency losses are present. The determination of *theoretical production time per unit* is based on continuous operation of the processing module, where the module is assumed to operate in an ideal condition. For equipment cycles that simultaneously process more than one unit, *theoretical production time per unit* is the minimum time to perform the cycle on an equipment load whose size is optimized for throughput divided by the number of units in that optimized load (CSM 21 and 42).

5.1.31 *theoretical throughput rate* — the smaller of the *bottleneck throughput rate* and the quotient of the *WIP capacity* divided by the *theoretical cycle time* (gives an unreachable upper bound on the factory throughput rate). See Equation 21.

5.1.32 *theoretical unit throughput by recipe (units per time)* — for a given production recipe, the number of units per period of time that theoretically could be processed by the equipment. For each recipe, theoretical unit throughput is equal to the reciprocal of theoretical production time per unit. [SEMI E79]

5.1.33 *throughput rate* — the number of units of production that pass through a process per period of time.

5.1.34 *throughput-rate and cycle-time efficiency* — the *best-case cycle time* divided by the *average cycle time* (shows the relative performance of the factory with respect to throughput rate and cycle time). See Equation 13. See § R1-1.6 in Related Information 1 for a discussion of this metric.

5.1.35 *total time* — all time (at the rate of 24 hours per day, seven days per week) during the period being measured. In order to have a valid representation of *total time*, all six basic equipment states must be accounted for and tracked accurately. [SEMI E10]

NOTE 8: For factory-level productivity metrics, total time should be larger than the average cycle time (and is recommended to be twice as large as the average cycle time and larger than the cycle time of any individual unit in finished units out).

5.1.36 *unit (of production)* — the basic entity in the factory (such as a wafer in a fab, a glass pane in a flat panel factory, or a die in a post-wafer back-end chip production facility) which acts as a product substrate (and moves through the factory with no assembly or disassembly processes). Only product units are included (as opposed to test wafers or other non-product devices).

NOTE 9: This definition is more restrictive than that given in SEMI E10 in order to be sufficiently specific.

NOTE 10: Production lot sizes can (and typically do) include multiple units of production, and units can (and typically do) contain multiple product devices (usually of the same type but possibly of different types). The user may chose to have the production lot be the *unit of production*, but that is not recommended because:

- the choice of lot size (and its inherent waiting time while its individual units are serially processed) would no longer be a relevant factor in evaluating how well the factory is running,
- lots can vary in size (even in the same factory),
- the meaning of *unit* would be inconsistent with other SEMI Standards, and
- *scrapped units out* would not be properly accounted for.

5.1.37 *uptime (equipment uptime)* — the hours when the equipment is in a condition to perform its intended function. It includes productive, standby, and engineering time, and does not include any portion of non-scheduled time. [SEMI E10]

5.1.38 *volume efficiency* — the *normalized production efficiency* times the *balance efficiency* (measures the total efficiency of the process with respect to factory dynamics). See Equation 2.

[1] *CSM 21: Closed-Loop Measurement of Equipment Efficiency & Capacity*, 1995: and *CSM 42: Productivity Metrics for Flexible-Sequence Cluster Tools*, 1998; Engineering Systems Research Center, University of California, Berkeley; http://esrc.berkeley.edu/csm/csmreports.html.

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5.1.39 *WIP capacity (W_{max})* — the maximum number of units of production the factory can contain (including on shelves, in stockers, on material handling transport vehicles, on equipment load ports, in internal carrier buffers, and in process chambers).

NOTE 11: This is not a practical WIP level, because it represents total gridlock of the factory.

5.1.40 *WIP efficiency* — the quotient of the smaller of the *critical WIP* and the *average WIP* divided by the larger of the two (measures the efficiency of *WIP* levels with respect to factory dynamics). See Equation 14.

5.1.41 *WIP turnover* — the *finished units out* divided by the *average WIP* (shows how often the inventory of work in process was replaced during the period being measured). See Equation 22.

5.1.42 *work in process* (*WIP*) — the number of units of production that have been released into the factory but have not yet been scrapped, sent out for external rework, or finished processing through all of their production steps.

5.1.43 *yield efficiency* — the *line yield* times the *test yield* (shows overall material efficiency). See Equation 3.

NOTE 12: This metric is similar to (but not the same as) the *quality efficiency* metric (see ¶ 5.1.21) from SEMI E79.

6 Calculated Metrics

6.1 Figure 1 shows how the terms defined in § 5 feed into each other. Arrows go from subordinate terms to the term in which they are cited as a part of the primary definition. Shown in the top row (in red rounded rectangles) are the basic building-block metrics for which no equations are needed in this Guide; the remaining metrics have their equation numbers given. At the very bottom is the overall factory efficiency metric into which almost everything feeds, although many of its subordinate terms are useful in their own right (if data availability or reliability is a problem). Along the left side (in green rounded rectangles) are the quality metrics that show the efficiency of the process with respect to use of materials. The remainder of the metrics (in blue rectangles) are production metrics that show the efficiency of the process with respect to factory dynamics (without the effects of yield and scrap losses). Related Information 1 gives an exposition of the underlying science behind these production metrics.

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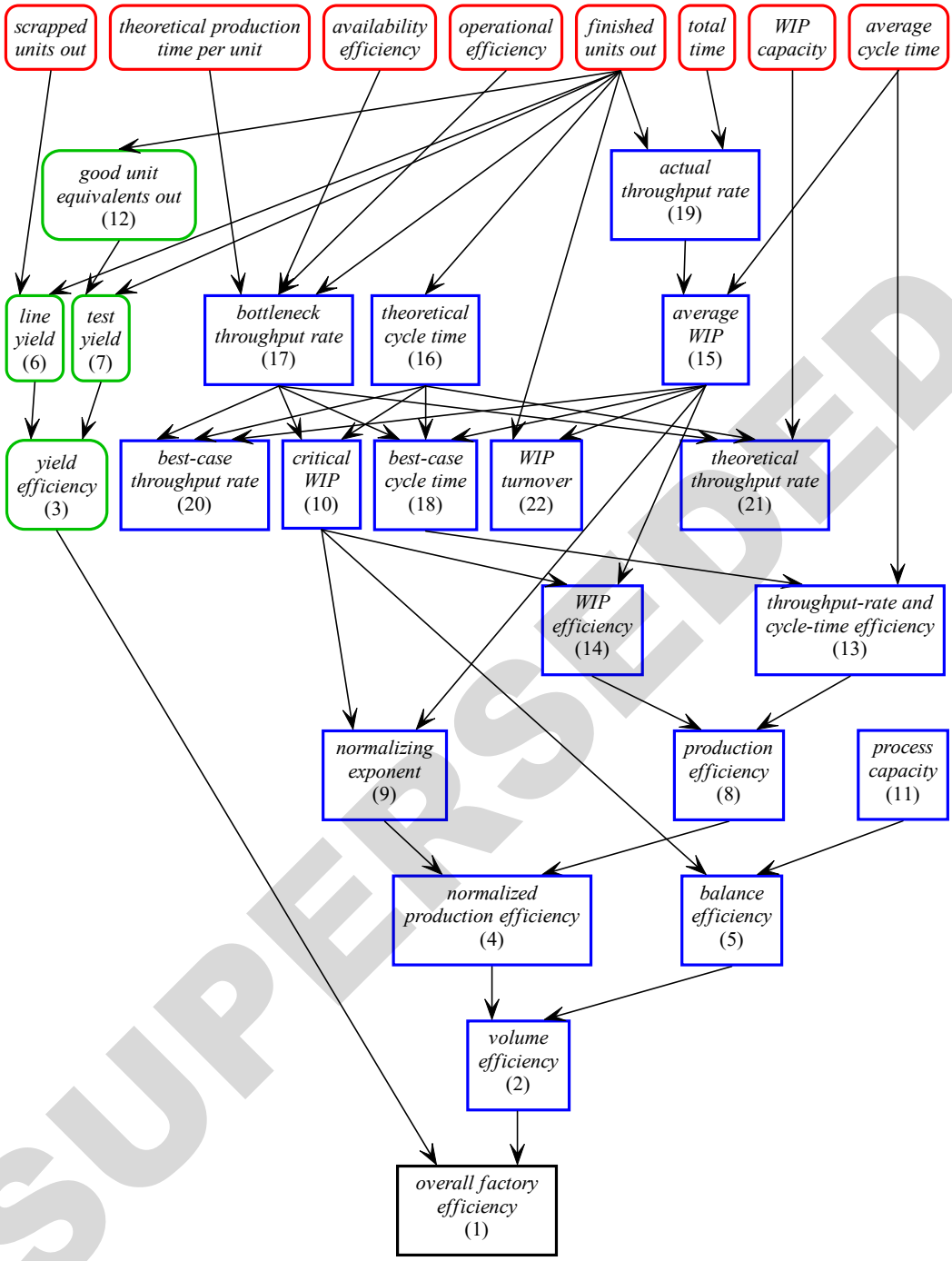

Figure 1
Definition Tree for Factory-Level Productivity Metrics

6.2 Unlike OEE, OFE and its factors are not dimensioned in time divided by time, because not all equipment in the factories is present or operating for the same amount of time. Similar to OEE, this metric:

- is dependent on product mix, process flow, operations, and time period, so be aware of this when comparing different factories or even comparing different time periods in the same factory when the product mix or process has changed (although such comparisons are still valid) especially when the factory variability is due to external factors (such as demand or excess capacity in non-bottleneck equipment).

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- does not comprehend down-stream demand or the varying importance of different products (which might be addressed by a separate metric).
- varies between zero (total chaos or gridlock) and one (unobtainable perfection).
- is a product of dimensionless efficiencies.

$$\begin{pmatrix} overall\ factory \\ efficiency \end{pmatrix} = \begin{pmatrix} volume \\ efficiency \end{pmatrix} \times \begin{pmatrix} yield \\ efficiency \end{pmatrix} \tag{1}$$

$$\begin{pmatrix} volume \\ efficiency \end{pmatrix} = \begin{pmatrix} normalized \\ production \\ efficiency \end{pmatrix} \times \begin{pmatrix} balance \\ efficiency \end{pmatrix} \qquad 2)$$

$$\begin{pmatrix} yield \\ efficiency \end{pmatrix} = \begin{pmatrix} line \\ yield \end{pmatrix} \times \begin{pmatrix} test \\ yield \end{pmatrix} = \frac{equivalent\ good\ units\ out}{\begin{pmatrix} finished \\ units\ out \end{pmatrix} + \begin{pmatrix} scrapped \\ units\ out \end{pmatrix}} \tag{3}$$

$$\begin{pmatrix} normalized \\ production\ efficiency \end{pmatrix} = \begin{pmatrix} production \\ efficiency \end{pmatrix}^{\begin{pmatrix} normalizing \\ exponent \end{pmatrix}} \tag{4}$$

$$\begin{pmatrix} balance \\ efficiency \end{pmatrix} = \frac{critical\ WIP}{process\ capacity} \tag{5}$$

$$\begin{pmatrix} line \\ yield \end{pmatrix} = \frac{finished\ units\ out}{\begin{pmatrix} finished \\ units\ out \end{pmatrix} + \begin{pmatrix} scrapped \\ units\ out \end{pmatrix}} \tag{6}$$

$$\begin{pmatrix} test \\ yield \end{pmatrix} = \frac{good\ unit\ equivalents\ out}{finished\ units\ out} \tag{7}$$

$$\begin{pmatrix} production \\ efficiency \end{pmatrix} = \begin{pmatrix} throughput\text{-}rate \\ and\ cycle\text{-}time \\ efficiency \end{pmatrix} \times \begin{pmatrix} WIP \\ efficiency \end{pmatrix} \tag{8}$$

$$\begin{pmatrix} normalizing \\ exponent \end{pmatrix} = \frac{1}{\log_2 \left[\frac{\begin{pmatrix} average \\ WIP \end{pmatrix} + \begin{pmatrix} critical \\ WIP \end{pmatrix} - 1}{\min\left\{ \begin{pmatrix} average \\ WIP \end{pmatrix}, \begin{pmatrix} critical \\ WIP \end{pmatrix} \right\}} \right]} \tag{9}$$

NOTE 13: For $x>0$, $\log_2(x) = \log_{10}(x)/\log_{10}(2) = \ln(x)/\ln(2)$.

$$\begin{pmatrix} critical \\ WIP \end{pmatrix} = \begin{pmatrix} theoretical \\ cycle\ time \end{pmatrix} \times \begin{pmatrix} bottleneck \\ throughput\ rate \end{pmatrix} \tag{10}$$

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