

SEMI E79-0200

STANDARD FOR DEFINITION AND MEASUREMENT OF EQUIPMENT PRODUCTIVITY

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NOTE: This document was rewritten in its entirety in 2000.

1 Purpose

1.1 The document provides metrics for measuring equipment productivity.

2 Scope

2.1 The document defines metrics and calculations for measurement of equipment productivity.

2.2 In the context of this document, it is important to note that “equipment productivity” is impacted greatly by factors far beyond the equipment itself, including (operator, recipe, facilities, material availability, scheduling requirements, etc.).

2.3 Effective application of this standard requires that equipment performance is tracked using the metrics for Equipment Reliability, Availability, and Maintainability (RAM) established in SEMI E10. Additionally, the Automated Reliability, Availability, and Maintainability Standard (ARAMS) SEMI E58 can be used for equipment with ARAMS capability. Productivity metrics for flexible-sequence cluster tools require tracking of SEMI E10 equipment states and recipes at the level of individual processing modules. Productivity performance of a flexible-sequence cluster tool is then calculated as the aggregate productivity performance of its individual processing modules.

2.4 This document is currently limited to measuring equipment productivity using Overall Equipment Efficiency (OEE) as the metric, and does not address the impact of productivity changes on cost, cycle time, or other measures. This document does not address any RAM issues over and above those in SEMI E10.

2.5 The previous SEMI E79 Standard (SEMI E79-0299) defined measurement of an Overall Equipment *Effectiveness* metric. In this revision of SEMI E79, the Overall Equipment Effectiveness metric has been renamed Overall Equipment *Efficiency*. The important differences include (1) the efficiency metric is expressed entirely in terms of time, while the effectiveness metric involved both factors expressed in terms of time and factors expressed in terms of

production units, and (2) the efficiency metric is applicable to flexible-sequence cluster tools, while the effectiveness metric was not. The Overall Equipment Efficiency metric is a better estimate measure of true equipment efficiency, and it is applicable for the efficiency assessment of all semiconductor processing equipment.

2.6 This standard does not purport to address safety issues, if any, associated with its use. It is the responsibility of the users of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

3 Referenced Standards

3.1 SEMI Standards

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

SEMI E38 — Cluster Tool Module Communications (CTMC)

SEMI E40 — Standard for Processing Management

SEMI E42 — Recipe Management Standard: Concepts, Behavior, and Message Services

SEMI E58 — Automated Reliability, Availability, and Maintainability Standard (ARAMS): Concepts, Behavior, and Services

3.2 Other Documents

CSM 21: Closed-Loop Measurement of Equipment Efficiency and Equipment Capacity; Engineering Systems Research Center, University of California, Berkeley, 1997.

CSM 42: Productivity Metrics for Flexible-Sequence Cluster Tools; Engineering Systems Research Center, University of California, Berkeley, 1998.

NOTE 1: As listed or revised, all documents cited shall be the latest publications of adopted standards.

4 Terminology

4.1 Terminology Applicable to Computation of the OEE Metric

4.1.1 *actual unit output* (units) — the number of units processed by the equipment during production time.

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

4.1.3 *cluster tool* — a manufacturing system made up of integrated processing modules mechanically linked together (the modules may or may not come from the same supplier) (SEMI E10).

4.1.4 *downtime (equipment downtime)* (time) — the time when the equipment is not in a condition, or is not available, to perform its intended function. It does not include any portion of non-scheduled time (SEMI E10).

4.1.5 *effective unit output* (units) — the number of units processed by the equipment during production time that were of acceptable quality, i.e., actual unit output less equipment assignable rework and equipment assignable scrap.

4.1.6 *equipment-assignable rework* (units) — any units being reworked due to a fault or defect assignable to the subject equipment. The units may be reworked at the equipment where the fault or defect occurred, or at other equipment.

4.1.7 *equipment-assignable scrap* (units) — any units that are permanently removed from production due to a fault or defect assignable to the subject equipment. The units may be removed from production at the operation where the fault or defect occurred, or at a subsequent operation.

4.1.8 *fixed-sequence cluster tool* — a cluster tool in which all units of production visit all processing modules making up the tool in a fixed sequence (CSM 42).

4.1.9 *flexible-sequence cluster tool* — a cluster tool in which the units of production visit a subset of the processing modules of the tool in sequences that may vary from unit to unit. In such tools, the processing modules that are engaged in processing activity vary from unit to unit according to dispatching decisions made by software internal to the tool (CSM 42).

4.1.10 *non-scheduled time* (time) — time when the equipment is not scheduled to be used in production (SEMI E10).

4.1.11 *operational efficiency* (time divided by time) — the fraction of equipment uptime that the equipment is processing actual units.

4.1.12 *operations time* (time) — total time minus non-scheduled time (SEMI E10).

4.1.13 *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 (CSM 21).

NOTE 2: The overall equipment efficiency metric accounts for all losses that reduce equipment performance from its maximum potential performance taking the existing equipment design and recipe specifications as given.

4.1.14 *performance efficiency* (time divided by time) — the fraction of equipment uptime that the equipment is processing actual units at theoretically efficient rates.

4.1.15 *processing module* — an indivisible production entity within an equipment system, e.g., a processing chamber or station within a cluster tool.

4.1.16 *processing module recipe* — all processing steps of a recipe performed within a single processing module without requiring reloading of that processing module (CSM 42).

4.1.17 *production time* (time) — sum of all periods of time in which a processing module is performing its intended function. For a non-cluster tool, a fixed-sequence cluster tool or an individual processing module within a flexible-sequence cluster tool, production time is equivalent to the SEMI E10 productive time for that entity. For a flexible-sequence cluster tool, production time is the aggregate of the production times for all processing modules encompassed by the cluster tool (CSM 42).

4.1.18 *productive state* — a period of time (*production time*) when the equipment is performing its intended function (SEMI E10).

4.1.19 *quality efficiency* (time divided by time) — the theoretical production time for Effective Units divided by the theoretical production time for Actual Units.

4.1.20 *rate efficiency* (time divided by time) — the fraction of production time that equipment is processing actual units at theoretically efficient rates.

4.1.21 *recipe* — the pre-planned and reusable portion of the set of instructions, settings, and parameters under control of a processing agent that determines the processing environment seen by the material. *Recipes* may be subject to change between runs or processing cycles (SEMI E38, SEMI E40, SEMI E42).

4.1.22 *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, CSM 42).

NOTE 3: Theoretical production time per unit varies by recipe.

4.1.23 *theoretical production time* (time) — production time during a period that is theoretically required to complete the unit quantities of the production recipes undertaken during the period. Theoretical production time is computed as the aggregation over all recipes of the theoretical production time per unit for the recipe applied to the unit quantity of that recipe (CSM 21, CSM 42).

NOTE 4: For flexible-sequence cluster tools, theoretical production time is the aggregate of the theoretical production times for the set of processing modules.

4.1.24 *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.

4.1.25 *total time* (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). For a flexible-sequence cluster tool, total time is defined as the aggregate total time of the set of processing modules encompassed by the cluster tool (CSM 42).

4.1.26 *unit* — any wafer, die, packaged device, or piece part thereof (includes product and non-product units) (SEMI E10).

4.1.27 *uptime (equipment uptime)* (time) — the hours when the equipment is in a condition to perform its intended function. It includes *production*, *standby*, and *engineering time*, and does not include any portion of *non-scheduled time* (SEMI E10). For a flexible-sequence cluster tool, uptime is defined as the aggregate uptime of the set of processing modules encompassed by the cluster tool (CSM 42).

4.1.28 *virtual machine* — an individual processing module within a flexible-sequence cluster tool, in combination with the transport module(s) serving that processing module. A flexible-sequence cluster tool has

one virtual machine defined for each of its processing modules (CSM 42).

4.2 Terminology Applicable to Computation of Additional Productivity Metrics Defined in Appendix 2

4.2.1 *demand equipment efficiency (DEE)* (time divided by time) — a measure of equipment productivity during the time that products are planned to be available to process at the equipment.

NOTE 5: *DEE* is based on theoretical production time for effective units and the portion of operations time that excludes planned no product time. A factory model or production schedule that defines the expected or planned idle time at the equipment is required to calculate *DEE*.

4.2.2 *engineering overall equipment efficiency (E-OEE)* (time divided by time) — a measure of equipment productivity assuming process specifications are optimized for minimum production time.

NOTE 6: *E-OEE* is based on the *engineering theoretical production time per unit* and *total time*.

4.2.3 *engineering theoretical production time per unit (ETHT)* – (time per unit) – the theoretical time required to process a given recipe assuming the recipe specification is optimized for minimum production time. *ETHT* is based on minimum durations for the objective processing steps, e.g., implant time for ion implant systems, plus minimum allowances for any additional supporting process steps, e.g., heating, cooling, gas stabilization, that are deemed absolutely necessary.

NOTE 7: *ETHT* must be defined to be less than or equal to the corresponding *theoretical time per unit (THT)* used in calculating *OEE*.

4.2.4 *equipment down no product time* (time) — the period of *equipment downtime* during which there are no units available at the equipment to process.

4.2.5 *intrinsic equipment efficiency (IEE)* (time divided by time) — a measure of equipment productivity that considers the combined effect of rate efficiency losses, recipe design, and equipment design.

NOTE 8: *IEE* is based on *value-added in-process theoretical production time for actual units* and *production time*.

4.2.6 *no product time* (time) — the period of *standby time* that the equipment is idle because there are no units available at the equipment to process.

4.2.7 *planned no product time* (time) — the period of *operations time* that the factory model or production schedule expects the equipment to be idle because there are no units available to process at the equipment.

4.2.8 *production equipment efficiency (PEE)* (time divided by time) — a measure of equipment

productivity during the time that products are available to process at the tool.

NOTE 9: One application of *PEE* is to measure the productivity of non-constraint tools that are expected to have periods of idle time due to lack of available work. *PEE* is based on *theoretical production time for effective units* and the portion of *operations time* that excludes *no product time* and *equipment unavailable no product time*.

4.2.9 reference overall equipment efficiency (R-OEE) (time divided by time) — a measure of equipment productivity relative to a benchmark theoretical production time.

NOTE 10: R-OEE is based on the reference theoretical production time per unit and total time.

4.2.10 reference theoretical production time per unit (RTHT) (time per unit) — the theoretical time required to process a given recipe on benchmark equipment (i.e., the fastest equipment model of similar type), for a benchmark product and process design.

NOTE 11: *RTHT* must be defined to be less than or equal to the corresponding *theoretical time per unit (THT)* used in calculating *OEE*.

4.2.11 value-added in-process overall equipment efficiency (VA-OEE) (time divided by time) — a measure of equipment productivity assuming all time except the value-added portion of processing cycles is wasted equipment time.

NOTE 12: VA-OEE is based on the *value-added in-process theoretical production time per unit* and *total time*.

4.2.12 value-added in-process theoretical production time per unit (VTHT) (time per unit) — theoretical production time per unit that credits only the objective processing steps that add value to products.

NOTE 13: *VTHT* must be defined to be less than or equal to *engineering theoretical production time per unit (ETHT)* used in calculating engineering OEE (*E-OEE*).

5 Equipment Productivity Measurement

5.1 The OEE calculation has been stated in terms that are consistent with SEMI E10. Reference may be made to Figure 1.

5.1.1 Figure 2 indicates how total time may be divided into portions representing theoretical production time for effective units and various sources of productivity loss. The domain for productivity improvement of all losses except operational efficiency is shared between the equipment supplier and equipment user. Productivity improvement of operational efficiency is the exclusive domain of the equipment user.

5.1.2 The formulas introduced in this section require as inputs the following fundamental quantities: total

time, equipment uptime, production time, and theoretical production time. Sample calculations for each of the formulas are provided in Appendix 1.

5.1.3 For efficiency measurement of individual processing modules or of fixed-sequence cluster tools, the fundamental quantities may be tallied in a straightforward manner, and consequently the formulas of this section may be applied in a straightforward fashion.

5.1.4 For efficiency measurement of flexible-sequence cluster tools, determination of the fundamental quantities requires more involved calculations. Formulas are provided in Section 6 for computing the fundamental quantities for flexible-sequence cluster tools. These fundamental quantities then may be used as inputs to the formulas of this section to compute the efficiency of a flexible-sequence cluster tool.

5.1.5 Additional supplemental efficiency metrics that will enable users to assess more specific aspects of equipment productivity are:

- Reference OEE,
- Engineering OEE,
- Value-Added In-Process OEE,
- Demand Equipment Efficiency,
- Production Equipment Efficiency, and
- Intrinsic Equipment Efficiency.

Definitions and formulas for these metrics are presented in Appendix 2.

5.2 Overall Equipment Efficiency (OEE) — The fraction of total time that equipment is producing effective units at theoretically efficient rates

$$\begin{aligned} \text{Overall Equipment Efficiency (OEE)} &= (\text{Theoretical Production Time for Effective Units}) \\ &\quad \div (\text{Total Time}) \\ &= (\text{Availability Efficiency}) \times (\text{Performance Efficiency}) \\ &\quad \times (\text{Quality Efficiency}) \end{aligned}$$

5.2.1 Availability Efficiency — The fraction of total time that the equipment is in a condition to perform its intended function.

$$\text{Availability Efficiency} = (\text{Equipment Uptime}) \div (\text{Total Time})$$

5.2.2 Performance Efficiency — The fraction of equipment uptime that the equipment is processing actual units at theoretically efficient rates.

$$\text{Performance Efficiency} = (\text{Operational Efficiency}) \times (\text{Rate Efficiency})$$

5.2.2.1 Operational Efficiency — The fraction of equipment uptime that the equipment is processing actual units.

$$\text{Operational Efficiency} = \frac{\text{Production Time}}{\text{Equipment Uptime}}$$

5.2.2.2 *Rate Efficiency* — The fraction of production time that equipment is processing actual units at theoretically efficient rates.

$$\text{Rate Efficiency} = \frac{\text{Theoretical Production Time for Actual Units}}{\text{Production Time}}$$

5.2.2.3 *Theoretical Production Time (for Actual Units or for Effective Units)* — Production time (for actual units or for effective units) during a period of observation that is earned at strictly theoretically efficient rates and assumes no efficiency losses.

$$\text{Theoretical Production Time for Actual Units} = \sum_i (\text{Actual Units of Recipe } i \times \text{THT}_i)$$

$$\text{Theoretical Production Time for Effective Units} = \sum_i (\text{Effective Units of Recipe } i \times \text{THT}_i)$$

where

THT_i = theoretical production time per unit of recipe_i

NOTE 14: Theoretical Production Time (for actual units or for effective units) may be calculated in terms of theoretical unit throughput by recipe.

$$\text{Theoretical Production Time for Actual Units} = \sum_i (\text{Actual Units of Recipe } i \div \text{UPH}_i)$$

$$\text{Theoretical Production Time for Effective Units} = \sum_i (\text{Effective Units of Recipe } i \div \text{UPH}_i)$$

where

UPH_i = theoretical unit throughput by recipe of recipe *i*

5.2.3 *Quality Efficiency* — The theoretical production time for Effective Units divided by the theoretical production time for Actual Units.

$$\text{Quality Efficiency} = \frac{\text{Theoretical Production Time for Effective Units}}{\text{Theoretical Production Time for Actual Units}}$$

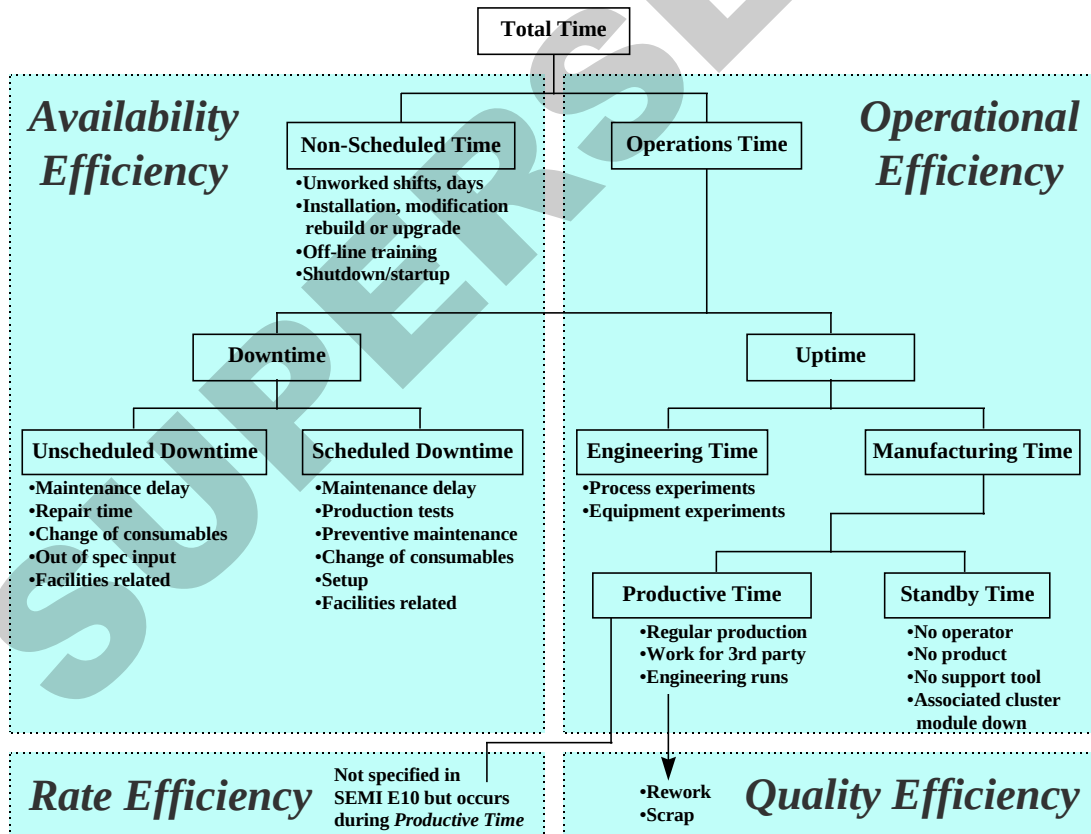


Figure 1
The Relationship Between SEMI E10 and OEE

E10 States

E79 Productivity Losses and Improvement Domains

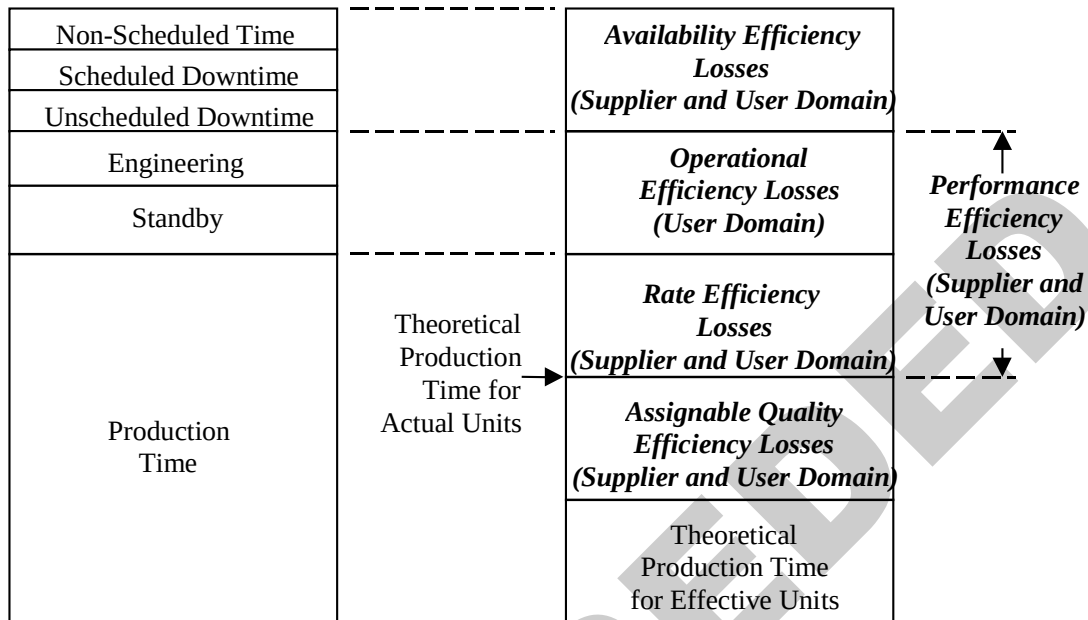


Figure 2
Stack Chart of Productivity Losses and Improvement Domains

6 Flexible-Sequence Cluster Tools

6.1 This section provides definitions and formulas applicable to flexible-sequence cluster tools for computing the following fundamental quantities: theoretical production time, production time, equipment uptime and total time. These quantities serve as inputs to the formulas of Section 5 for efficiency measurement.

6.1.1 Flexible-sequence cluster tool productivity is measured at the individual processing module level of detail according to a virtual machine model described in this section. Productivity performance for the entire flexible-sequence cluster tool is then calculated as the aggregate productivity performance of its individual processing modules.

NOTE 15: Evaluation of flexible-sequence cluster tool productivity does not necessarily apply to the evaluation of flexible-sequence cluster tool RAM.

6.2 Virtual Machine Model

6.2.1 A virtual machine is an individual processing module in combination with the transport mechanisms that serve that processing module. When a transport mechanism is engaged in a material handling operation that does not involve a particular processing module, it is not considered to be operating as part of the virtual machine defined for that processing module.

6.2.2 Theoretical production time per unit for a recipe is the sum of theoretical times for all required operational elements:

- Wafer loading,
- Elements occurring within a process module, and
- Wafer unloading.

6.2.2.1 Where appropriate, a combined loading and unloading time may be replaced with a single theoretical value for a *wafer exchange*.

6.3 *Fundamental Quantities for Processing Modules and Flexible-Sequence Cluster Tools* — This section defines fundamental quantities that are evaluated for individual processing modules and flexible-sequence cluster tools as inputs to the formulas presented in Section 5.0. In each case, the fundamental quantity is determined for each individual processing module within a flexible-sequence cluster tool. The equivalent fundamental quantity for the flexible-sequence cluster tool is the sum of the quantities for the individual processing modules.

NOTE 16: It is recognized that application-specific interactions between processing modules within flexible-sequence cluster tools may impose varying amounts of standby time on the individual processing modules. This approach treats these interactions as standby losses for the

flexible-sequence cluster tool and does not make any allowances for them in either production time or theoretical production time.

6.3.1 Theoretical Production Time (for Actual Units and for Effective Units)

6.3.1.1 *Processing Module Theoretical Production Time (for Actual Units and for Effective Units)* — Theoretical production time earned by an individual processing module according to the virtual machine model.

$$\begin{aligned} &\text{Processing Module} \\ &\text{Theoretical Production Time for Actual Units} = \\ &\quad \Sigma_i[(\text{Theoretical Production Time Per Unit} \\ &\quad \text{for Processing Module Recipe } i) \\ &\quad X (\text{Actual Units of Processing Module Recipe } i)] \end{aligned}$$

$$\begin{aligned} &\text{Processing Module} \\ &\text{Theoretical Production Time for Effective Units} \\ &= \Sigma_i[(\text{Theoretical Production Time Per Unit} \\ &\quad \text{for Processing Module Recipe } i) \\ &\quad X (\text{Effective Units of Processing Module Recipe } i)] \end{aligned}$$

6.3.1.2 *Flexible-Sequence Cluster Tool Theoretical Production Time (for Actual Units and for Effective Units)* — Aggregate theoretical production time earned by all processing modules according to the virtual machine model.

$$\begin{aligned} &\text{Flexible-Sequence Cluster Tool} \\ &\text{Theoretical Production Time for Actual Units} \\ &= \Sigma_j(\text{Theoretical Production Time} \\ &\quad \text{for Actual Units for Processing Module } j) \end{aligned}$$

$$\begin{aligned} &\text{Flexible-Sequence Cluster Tool} \\ &\text{Theoretical Production Time for Effective Units} \\ &= \Sigma_j(\text{Theoretical Production Time} \\ &\quad \text{for Effective Units for Processing Module } j) \end{aligned}$$

6.3.2 Production Time

6.3.2.1 *Processing Module Production Time* — The sum of all periods of manufacturing time in which a processing module or the transport module serving that processing module are performing operations according to the virtual machine model. When SEMI E10 equipment states are tracked at the virtual machine level, processing module production time is equivalent to *E10 productive time*. Automated tracking is required for accurate results.

6.3.2.2 *Flexible-Sequence Cluster Tool Production Time* — Aggregate production time for all processing modules tracked according to the virtual machine model.

$$\begin{aligned} &\text{Flexible-Sequence Cluster Tool Production Time} = \\ &= \Sigma_j(\text{Production Time for Processing Module } j) \end{aligned}$$

NOTE 17: In this quantity, elapsed times for transport operations that reposition units from one processing module to another are intentionally credited to both modules. Also note that this aggregate measure may be larger than the elapsed time observed and can only be compared with similar aggregate flexible-sequence cluster tool metrics.

6.3.3 Equipment Uptime

6.3.3.1 Equipment uptime is defined to measure the total time, during a period of observation, that a processing module or a flexible-sequence cluster tool is in a condition to perform processing in some form.

6.3.3.2 SEMI E10 defines equipment uptime as including E10 productive time, engineering time, and standby time. This definition applies to individual processing modules of a flexible-sequence cluster tool. For the flexible sequence cluster tool as a whole, production time is the sum of production times for the individual processing modules. This production time is used in lieu of productive time.

NOTE 18: This representation of flexible-sequence cluster tool equipment uptime is for productivity purposes only, and may not apply for the determination of flexible-sequence cluster tool RAM.

6.3.3.3 Processing Module Equipment Uptime

$$\begin{aligned} &\text{Processing Module Equipment Uptime} = \\ &\quad \text{Processing Module Production Time} \\ &\quad + \text{Processing Module Engineering Time} \\ &\quad + \text{Processing Module Standby Time} \end{aligned}$$

6.3.3.3.1 *Processing Module Engineering Time* — The sum of all periods of time in which a processing module is user-selected for the exclusive use of engineering product, process, and/or equipment experiments. Engineering time may be declared for one processing module without having to declare engineering time for all processing modules.

6.3.3.3.2 *Processing Module Standby Time* — The sum of all periods of manufacturing time not counted in production time, when the virtual machine is *capable* of starting new work.

6.3.3.4 Flexible-Sequence Cluster Tool Equipment Uptime

$$\begin{aligned} &\text{Flexible-Sequence Cluster Tool Equipment Uptime} = \\ &\quad \Sigma_j(\text{Processing Module Equipment Uptime} \\ &\quad \text{for Processing Module } j) \end{aligned}$$

6.3.4 Total Time

6.3.4.1 *Processing Module Total Time* — For individual processing modules, processing module total time is trivially defined as all time observed (at the rate of 24 hours per day and seven days per week).

6.3.4.2 Flexible-Sequence Cluster Tool Total Time

Flexible-Sequence Cluster Tool Total Time =

$$\sum_j (\text{Processing Module Total Time for Processing Module } j) =$$

(Total Time Observed) X (Number of Processing Modules)

7 Related Reference Material

Nakajima, S., Introduction to TPM: Total Productive Maintenance, Productivity Press, Cambridge, MA, 1988.

TPM in Process Industries; Edited by Tokutaroo Suzuki, Productivity Press, 1994. (Originally published as Sochi Kogyo no TPM: Japan Institute of Plant Maintenance, 1992).

TPM Encyclopedia; Edited by Japan Institute of Plant Maintenance, 1996.

TPM Focused Improvement: Loss Assessment Training Module, International SEMATECH, Available to International SEMATECH and SEMI-SEMATECH member companies, 1999.

TPM New Implementation Program in Fabrication and Assembly Industries, Edited by Kunio Shiroye, Japan Institute of Plant Maintenance, 1996.

Konopka, John M., Improvement Output in Semiconductor Manufacturing Environments, doctoral dissertation, Arizona State University, Tempe, Arizona, 1996.

Konopka, John., Trybula, Walt., Overall Equipment Effectiveness (OEE) and Cost Measurement, Proceedings of the 1996 IEEE/CPMT 19th International Electronics Manufacturing Technology Symposium, Austin, TX, USA, 1996.

Leachman, Robert C., Closed-Loop Measurement of Equipment Efficiency and Equipment Capacity, IEE Trans. Sem. Manuf. 10(1), 84097, 1997.

Busing, David P., Automated Procedures for Characterizing Specific Productivity Losses with Applications in the Semiconductor Manufacturing Industry, doctoral dissertation, University of California, Berkeley, 1998.

CSM-44: Performance Models of Theoretical and Average Process Times for Selected Semiconductor Fabrication Equipment; Engineering Systems Research Center, University of California, Berkeley, 1999.