Process Watch: Process Control and Production Cycle Time

By Douglas G. Sutherland and David W. Price

Author's Note: The Process Watch series explores key concepts about process control—defect inspection and metrology—for the semiconductor industry. Following the previous installments, which examined the 10 fundamental truths of process control, this new series of articles highlights additional trends in process control, including successful implementation strategies and the benefits for IC manufacturing.

In the early stages of development, having more process control can help reduce both the number and duration of cycles-of-learning (the iterations required to solve a particular problem). In high volume manufacturing a well-thought-out process control strategy can increase baseline yield and, at the same time, limit yield loss due to excursions. At all stages, an effective process control strategy is required to ensure that the fab is operating at its lowest possible cost. In addition to minimizing production costs, adding process control steps can, counterintuitively, also minimize cycle time.

Figure 1 shows a conceptual plot of how cycle time would vary as a function of the number of process control steps. On the left-hand side of the chart where there are no metrology and inspection (M&I) steps in place, the cycle time is effectively infinite. If a lot reaches the end of the line and has zero yield there is no way to isolate the problem. Theoretically one could isolate the problem by trial and error, but with only 100 process steps and only two parameters each, there would be 2^{100} (1.3×10^{30}) possible combinations. Even testing one parameter per second, it would take much longer than the age of the universe to exhaust all possible combinations of the parameter space.

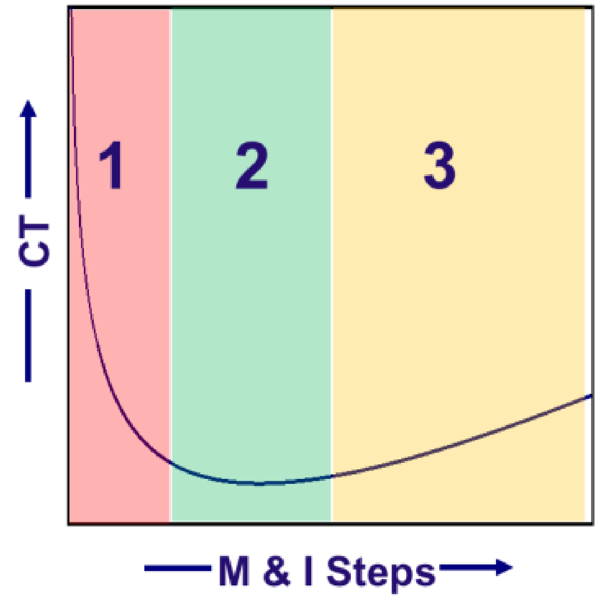

Figure 1. Cycle Time (CT) versus the number of process control (metrology and inspection) steps. In zone 1, the fab is information starved and unable to find yield excursions and isolate the underlying problems. In zone 3, the fab is getting more information than it can use. In zone 2, the fab has achieved balance – with a number of process control steps that minimizes the cycle time.

As process control steps are added the cycle time comes down from an effectively infinite value to some manageable number. At some point the cycle time will reach a minimum value. Beyond this point, adding in further process control steps will actually cause the cycle time to increase linearly with the number of added steps. The optimal amount of process control will always be a trade-off between minimizing cycle time, minimizing excursion cost, and maximizing baseline yield. The latter two usually have a much greater financial impact.

Adding process control steps can reduce a fab's cycle time, but how does that work? A full treatment of cycle time (Queuing Theory) is far beyond the scope of this article, however at a high level, it can be broken down into a few manageable components. The total cycle time (CT) is the sum of the queue time (the time a lot spends waiting for a process tool to become available) and the processing time itself. Since the processing time is fixed, the only way to reduce CT is to concentrate on the queue time (Q). From Queueing Theory it can be shown that Q can be expressed by the product of three separate functions[4],

$$Q = f(u)\, f(a)\, f(v) \qquad \text{eqn 1}$$

where $f(u)$, $f(a)$ and $f(v)$ are, respectively, functions of utilization, availability and variability. The first two functions will always be finite, therefore it becomes clear that $Q = 0$ only when $f(v) = 0$. Put another way, reducing variability in the fab reduces the queue time, and if we remove all variability from the system the queue time will drop identically to zero and the CT will be equal to just the processing time.

Figure 2 shows a plot of CT as a function of utilization for three different levels of variability: zero, medium and high. The Y-axis measures cycle time in units of total processing time called the X-factor. When the variability is zero all the lots move through the fab in lock-step; there is no increase in CT with increasing utilization and all tools could be run, theoretically, at 100 percent utilization. In this case the queue time is zero and the CT is equal to the total processing time for all the steps (CT=1). As soon as some variability is introduced, the CT starts to increase exponentially with utilization and the more variability there is, the more dramatic the increase becomes.

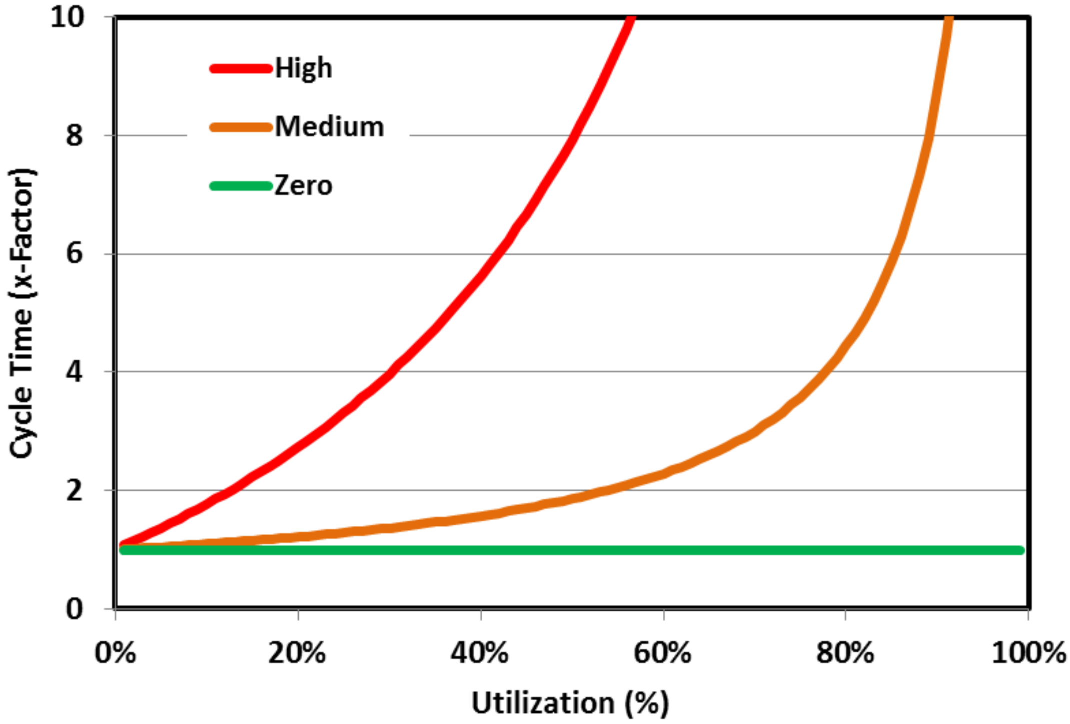

Figure 2. Cycle time versus Utilization for three different levels of variability: High, Medium and Zero.

Variability in the fab comes from many sources: in the lot arrival rate, in the frequency of maintenance requirements, and in the time required for that maintenance to be performed are just a few of the sources. An excursion—a lot that is out of control—affects all of the above.

Having more process control points will not immediately change the number of excursions in a fab but it will immediately improve the efficiency with which the fab reacts to them.

In fact, over time, having more process control points can also reduce the number of excursions because it increases a fab's rate of learning.

Consider a lot that has been flagged for having a defect count that was beyond the control limit for process step N. If, as shown in figure 3a, there was another inspection point between process steps N and N-1, then the problem can be immediately isolated. Only the tool at step N (the process tool the offending lot went through) needs to be put down and only the lots that went through that tool since the last good inspection need to be put on hold for disposition.

By contrast, consider what would happen in figure 3b where the last inspection point was five steps ago at process step N-5. Practices differ from fab to fab, however in the worst case scenario, all ten tools that the lot went through would be put down and all lots that went through any of those tools would have to be put on hold. Instead of a minor disruption involving a single process tool and a few lots, entire modules and dozens of lots can be directly affected. Indirectly, it affects the entire fab.

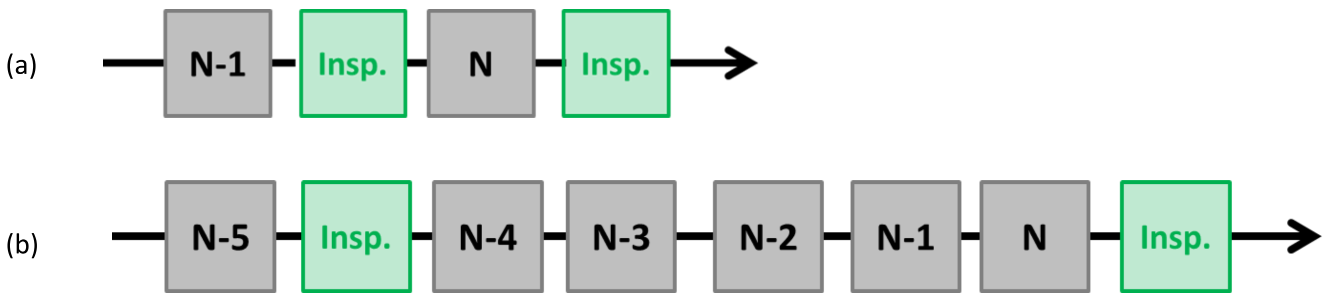

Figure 3. (a) One process step between inspection points. (b) Five process steps between inspection points.

Figure 3 shows that implementing fewer inspection steps has a threefold impact on cycle time:

1. More process tools are involved and must be taken offline
2. Each process tool is down for a much longer period of time because it takes longer to isolate the problem
3. More wafers are in the impacted section of the production line. These wafers must be dispositioned

The variability introduced by these three impacts will also propagate through the fab; they constrict the flow of work in progress (WIP) through the fab, creating a WIP bubble that affects the lot arrival rate (increased variability) at every station downstream. All of these factors contribute to fab-wide variability and because of the re-entrant nature of the process flow, they add to the cycle time of every single lot in the fab.

When an excursion occurs, the resulting disruption impacts the cycle time of every lot in the fab and it quickly becomes a vicious cycle. The more excursions that happen during a given lot's cycle time, the longer that cycle time will be. And the longer the cycle time is, the more likely it is that that lot will be in the fab when the next excursion occurs.

Adding inspection steps will add a small, known amount of cycle time to those lots that get inspected, but due to sampling (not every lot gets inspected) it will have a much smaller impact on the average. When an excursion does occur, comparatively few process tools will have to be put down and the module owner will be able to isolate the problem much sooner. The total disruption to the fab (the variability) will be reduced and the cycle time of all lots will be improved.

This counter-intuitive concept has been borne out by several fabs that have both added inspection steps and reduced cycle time simultaneously. Adding process control steps contributes to fab efficiency on several levels: accelerating R&D and ramp phases, increasing baseline yield, limiting the duration of excursions, and reducing cycle time. In short, a better-controlled process is a more efficient process.

The next article in this series will discuss the impact of process control to cycle time on so-called "hot lots" typically run during early ramp.

References:

1) "Process Watch: Fab Managers Don't Like Surprises," *Solid State Technology*, December 2014.
2) "Process Watch: Time is The Enemy of Profitability," *Solid State Technology*, May 2015.
3) "Economic Impact of Measurement in the Semiconductor Industry," Planning Report 07-2, National Institute of Standards and Technology, U.S. Department of Commerce, December 2007.
4) Hopp, W. J., and Spearman, M. L. *Factory Physics* (2nd ed.). (New York: Irwin, McGraw-Hill, 2001), 325.

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Dr. David W. Price is a Senior Director at KLA-Tencor Corp. Dr. Douglas Sutherland is a Principal Scientist at KLA-Tencor Corp. Over the last 10 years, Dr. Price and Dr. Sutherland have worked directly with more than 50 semiconductor IC manufacturers to help them optimize their overall inspection strategy to achieve the lowest total cost. This series of articles attempts to summarize some of the universal lessons they have observed through these engagements.