New Strategies
for Fab Productivity

Semiconductor growth has been fueled by consistent yearly reductions in cost-per-function over the last three decades (Figure 1). Historically, cost-per-function has been driven by design innovation, technology shrinks, and fab productivity. However, as the number of chip designs in production seems to be declining and manufacturing processes become more complex and challenging, greater emphasis is being placed on fab productivity as a key enabler of cost reduction. Extending the productivity trend now depends on the successful implementation of next generation fab solutions — novel approaches to architecture and operating methodologies — in new and existing factories.


This new development is also fueled by changes on the demand side of the IC industry. The semiconductor industry is being driven by consumer electronics. Achieving shorter product lifecycles, faster time to market and a high degree of cost sensitivity demands agile, low cost and lean manufacturing.

ALTERNATIVE STRATEGIES

Existing approaches to cost reduction are limited. The Giga Fab concept, for example, aims to reduce the cost-per-unit by invoking economies of scale, but requires a substantial financial outlay. This may be appropriate for very high-volume manufacturers, but is unsuitable for the numerous fabs and foundries that do not meet this criterion. Similarly, wafer size conversions have historically been coupled with significant improvements in factory automation and equipment capability, resulting in higher yields and improved equipment productivity. Transitioning to 450mm size wafers may provide cost benefits, but the productivity impact of this transition and its timing are debatable, and
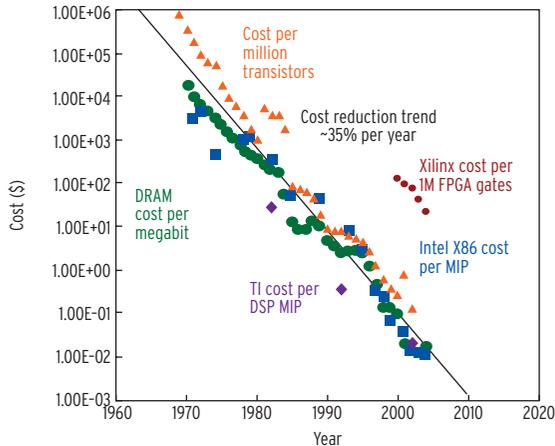
▲ **FIGURE 1.** Cost-per-function historical trend. (Source: IC Knowledge LLC)

the investments required may be prohibitive. An alternative that holds much promise for high productivity gains with lower risk is 300mm Prime, the umbrella term for next-generation factory improvements for 300mm fabs. In this article, we explore the manufacturing productivity improvements being considered for 300mm Prime.

THE DEFINITION OF PRODUCTIVITY

Historically, the IC industry has defined productivity improvement in terms of maximizing output, as shown in the numerator of the relationship in Figure 2. This limited view of productivity fails to consider sources of "waste" in the fab, such as delays in cycle time (CT), energy and other natural resources. The correct definition of productivity that can provide a more useful and realistic view of fab performance should balance outputs and inputs, and include the amount of time and energy that is wasted in the fab.
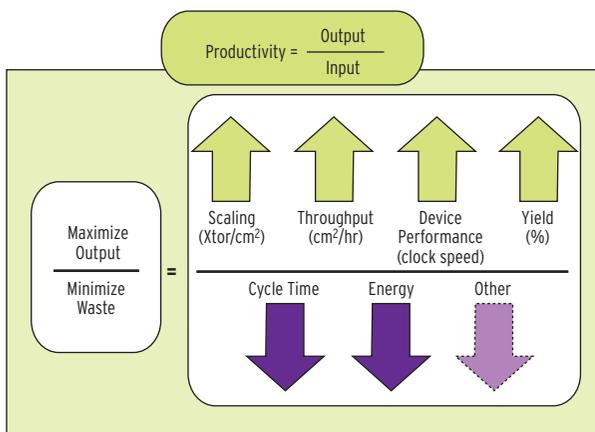
The Production System Design (PSD) lab at MIT defines the goals of lean manufacturing as, "… aimed at the elimination of waste in every area of production including customer relations, product design, supplier networks and factory management." Eradicating waste is one of the key elements in increasing fab productivity.

For example, throughput can be increased and CT decreased by reducing non-productive time in the factory. A wafer can spend a significant amount of time waiting for other processes to complete, which is non-productive, or wasted time. For instance, the average non-hot lot may spend only about 30% of its time in the fab in process steps. Even within a step, most of the time is wasted: on a cluster tool only 10-25% of the wafers in a 25-wafer lot may be in process or in transit at one time. In other words, 75-90% of the wafer's time at the tool is still spent waiting, either before or after processing. Combined, wafers may spend 85% to 95% of the time non-productively.

In this article, we explore the relationship between fab throughput and CT along with strategies on how to optimize a factory to maximize throughput and minimize cycle time.

FACTORY DYNAMICS

To examine the sources of waste and non-optimized production, it is necessary to examine the dynamics of product flow through the factory. Movement of product in a factory can be expressed by Little's Law:

$$\text{WIP} = \text{THROUGHPUT} \times \text{CYCLE TIME}$$

This equation describes the relationship between fab throughput (wafers/day) and CT (days), where WIP = work in progress.

Figure 3 illustrates the relationship between throughput and WIP under different scenarios based on a simulated model. Fab throughput is limited by the constraint

▲ **FIGURE 2.** Productivity defined as maximizing output and minimizing waste.
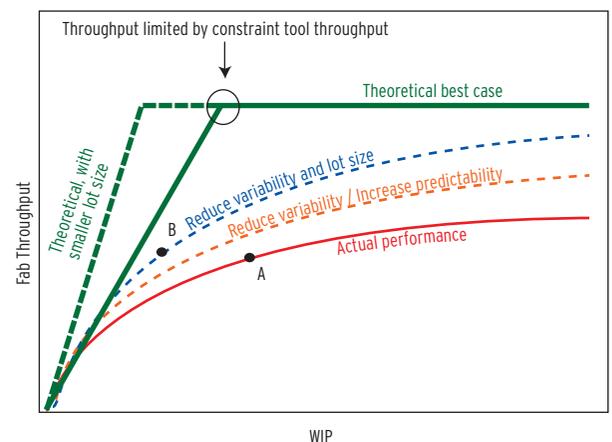
▲ **FIGURE 3.** Illustration of the relationship between throughput and WIP.

toolset (green curve): tool utilization and fab throughput can increase by raising the WIP inventory until the constraint is reached. Actual fab throughput (red curve) is much lower than the theoretical best case because of variability and flow dynamics.

One important source of variability relates to tool availability. Overall tool availability is an insufficient metric in predicting throughput because it is an average over time. It is as important that the tool be available at the specific moment when the lot arrives, even if the overall availability is unchanged. By reducing unscheduled downs and repair time variability, the tool is more likely to be available when the lot arrives, contributing to a net increase in fab throughput (orange curve). Note: Computerized maintenance management software (CMMS) addresses the problem of preventive maintenance of tools to deliver higher levels of tool utilization by scheduling PMs on the tool ahead of actual part failures. Additionally, combining inventory management modules with the manufacturing execution system (MES) ensures that when tools are scheduled for a PM, the right part is available when it is needed to reduce the downtime.

Recent analytical work shows that lot size impacts variability and non-productive time. Larger lot sizes, as well as the use of batch tools, typically leads to localized WIP buildups while smaller lot sizes and single-wafer equipment result in a smoother flow through the manufacturing line. With smaller lot sizes the predictability of lot arrival improves and wait time decreases. Consequently, a higher fab throughput for the same WIP can be expected (blue curve). Further improvements—beyond the blue curve—could be realized via the MES and predictive scheduling. Material handling systems need to address the challenges of smaller lot size transport requirements in a smaller lot environment. The goal for these systems has been and remains: right wafer at the right tool at the right time.

SOLUTIONS FOR IMPROVING PRODUCTIVITY

Minimizing variability and non-productive time to achieve 300mm factory productivity improvements will require a renewed emphasis on managing CT and advancing equipment and process control. With a concerted effort to boost productivity, the industry can continue to drive down cost-per-function to meet market requirements. Several solutions exist to meet these objectives through a combination of software, hardware and production methodologies (Table 1).

Non-productive time and variability are reduced when excursions are resolved faster. The typical method of detecting excursion is wafer-based sampling. However, this method is reactive and inherently slow. By contrast, "smart tools" accelerate problem identification and resolution. We have developed smart tools with algorithms for closed loop advanced equipment control (AEC) and advanced process control (APC) by providing on-tool, real-time data acquisition systems. Run-to-run APC (R2R APC) and AEC help to reduce the frequency of excursions. With R2R control, variability of on-wafer parameters such as film thickness, sheet resistance, etc. is reduced.

Fault detection and classification (FDC) capability can be used as a real-time equipment monitor and alarm system to provide faster root cause analysis of excursions and yield issues. FDC uses multivariate algorithms to detect subtle interactions between variables and reduces the time to take corrective action by comparing actual faults to signatures of known faults. Remote access and analysis of tool variables assisted by FDC allows even faster resolution of

Improvement Solutions	Variability	Non-Productive Time
Equipment predicability	✓	✓
Equipment engineering systems (FDC, APC, etc.)	✓	✓
Equipment remote service	✓	✓
Switch from batch to cluster tools		✓
Small lot size	✓	✓
Factory optimization software tools	✓	✓
Lean manufacturing methods		✓

▲ TABLE 1. Solutions to drive down variability and non-productive time.

FAB PRODUCTIVITY SOLUTIONS

CATEGORY	BENEFIT	APPLIED MATERIALS SOLUTIONS
Equipment performance optimization	Higher throughput Good on-wafer results	Industry-leading technology in highly productive toolset
Equipment predictability	Reduced cycle time Load balancing Inventory management Preventive maintenance	Equipment-level AEC/APC closed loop control scheme and algorithms E3 (Enterprise Equipment Engineering) Xsite
Technology extendibility	Process control/ Cpk Reduced defects Longer tool lifetime	Process engineering System enhancement
Output optimization	Fab capacity increase Increased constraint tool output Reduced cycle time Lower cost of ownership Better labor efficiency	Remote expert maintenance (RSO) FDC & APC EPT, Xsite, AutoSched AP RTD Predictive scheduling
Small lot manufacturing	Reduced cycle time Demand driven production linking shop floor to business systems	Competitive single-wafer process tools MES capability including single lot/single wafer tracking FAB300 FACTORYworks
Excursion management	Reduced excursions Reduced variability	Process engineering FDC R2R APC/AEC
Multi-site execution control	Enterprise wide asset utilization across fabs Manage global wafer starts across fabs	MES FACTORYworks FAB300
Environmental solutions	Reduced energy usage Reduced water usage Reduced effluents	Energy-efficient tool design Abatement solutions Energy efficiency solutions Wafer reclaim

faults and unscheduled events by involving tool experts, regardless of physical location.

It is not sufficient to reduce variability and non–productive time for each tool individually. To reduce CT and increase throughput for the entire fab, it is necessary to optimize how the tools operate in concert with each other. Identification and allocation of resources to constraint tools increase net fab productivity. Performance throughput optimization (PTO) software tools that address the entire factory (see sidebar) can be immensely helpful in this task by executing, simulating, analyzing and visualizing the movement of inventory across the fab and identifying bottlenecks.

Finally, small lot manufacturing and the shift from batch to single wafer processing increase the predictability of wafer arrival by smoothing and distributing the flow of product over time, resulting in lower CT and higher output.

Adoption of these and other solutions allows fabs to overcome the problem illustrated by the red curve in Figure 3: Throughput cannot be increased without building up WIP and thus increasing CT. The implementation of next–generation factory solutions (Table 1) for variability reduction can move fabs up to the blue curve and beyond. As illustrated in the possible shift from Point A to Point B, fab utilization (Figure 3), can be increased while reducing WIP and thus CT.

CONCLUSION

Productivity gains are essential to achieving the cost and time reductions demanded by markets. In order to be successful, we must pursue fab productivity gains with a focus on eradicating waste in the fab. Fortunately, solutions are already available that can deliver significant productivity gains. Deploying these productivity solutions can provide a faster ROI for fabs compared to more drastic solutions such as transitioning to a larger wafer size. ■

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