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SIZING A PILOT PRODUCTION LINE USING SIMULATION

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ABSTRACT

The semiconductor industry is rapidly expanding worldwide. With the continuing advancement of technology, companies are continually striving to develop and maintain cutting edge products to stay "ahead of the curve." As a result, old and new companies alike often have the need to develop pilot production lines to test new engineering and processing ideas. We present a case study example of how simulation can be used to establish the initial tooling and operator requirements for pilot production lines, as well as to estimate the fixed and recurring costs associated with the line.

1 INTRODUCTION

The manufacture of semiconductors is a global, multi-billion dollar industry, with sales of over U. S. $204 billion for the year 2000 (Semiseek News 2001). The semiconductor industry is responsible for the manufacture of components for computers, communications equipment, as well as many other items. Product life cycles continue to decrease as companies strive to remain technologically competitive. The latest, greatest product today is all too often only a memory six months from now.

Current-generation semiconductor wafer fabrication facilities ("wafer fabs") manufacture semiconductors on silicon wafers that are 8" (200 mm) in diameter using a tool set that can cost well over U. S. $1 billion. The wafer fabs of the next generation will process 12" (300 mm) wafers on a highly automated tool set that could cost in excess of U. S. $2 billion. As a result, new pilot production lines for products must be designed and implemented quickly, as well as cost effectively, in order to assess both the processing and financial feasibility of proposed product and/or equipment changes.

When developing a pilot line, many uncertainties exist. Questions that high-level managers often want the answer to include, but are not limited to, the following:

- What is the expected operating cost of the proposed facility?
- How much capital investment will be required?
- What is the expected lot cycle times and work-in-process levels of each product that will be made in the factory?

In a traditional manufacturing line, these concerns may be addressed relatively easily by an experienced individual or team of individuals and the appropriate software tools, as current factory models and/or production data are often readily available. In some cases, it may even be possible to estimate these values with a spreadsheet.

However, estimation of these parameters is not quite as simple in the semiconductor industry. As Robinson and Giglio (1999) note, issues of setups, batching tools, reentrant flow and shared tools create tremendous difficulties when planning a new fab. Fortunately, semiconductor industry-specific simulation packages exist, which greatly aid in the design of useful models quickly and relatively cheaply.

The goal of this paper is to determine the required tools set and operator requirements for a proposed two-product pilot production line using simulation. We choose simulation instead of classic static capacity analysis due to our interest in estimating product cycle times and factory work-in-process (WIP) levels. The two products are to be manufactured simultaneously at three possible levels of demand: weak, average, and strong. These three levels were created to simulate tepid, normal, and aggressive adoption of our fictitious products. Each demand level is projected for five years of production, with a shift in product mix from Product 1 to Product 2 occurring during this timeframe. Toolset solutions found during our analysis must produce stable cycle times and acceptable work-in-process levels while maintaining affordable levels of cost.

The remaining sections of this paper are organized as follows. Section 2 describes in more detail the difficulties involved in modeling and scheduling semiconductor manufacturing facilities. Next, Section 3 discusses the simulation model and experimental data used in the research effort, followed by simulation results, including the tooling requirements, in Section 4. Finally, Section 5 presents the conclusions remarks about the pilot production line, as well as tooling and staffing requirements in general.

2 SEMICONDUCTOR MANUFACTURING

Semiconductor manufacturing, the process of building integrated circuits on silicon wafers, is amongst the most complex manufacturing processes performed today. Wafers travel through the wafer fab in groups of wafers, termed “lots”, completing between 200 to 500 processing steps depending on the product (job) type. Lot sizes vary from product to product but are frequently between 25 to 50 wafers.

The many processing steps of a product in a wafer fab are completed on many different tools. A fab with 50 to 100 tools is not uncommon, and each tool may run from U. S. $100,000 up to $7,000,000. Furthermore, each fab typically owns multiple machines of each tool type and operates them in parallel, dedicating some of those machines to specific product types. Tools process products using many different methods including single-wafer processing (photolithography is an example), lot-processing (wet sinks), and batch processing (diffusion furnaces) that may process several or more lots together.

Planning deployment of a production line in a wafer fab becomes quite difficult. Because of the extremely high cost of owning and operating wafer fabs, the traditional linear production line is not used. Instead product flow is recirculated through tool groups (termed “reentrant flow”) as required by the product “recipe”. Also, to deal with reliability (downtime) issues, machines are frequently operated in parallel. Sequence-dependent setups also appear in wafer fabs with the use of machines like ion implanters. A sequence-dependent setup is an amount of time that is required to properly prepare a machine for manufacturing which varies according to the previous and succeeding product types. Adding yet more complexity are individual lot (job) ready times and due dates. When all of these items combine in a manufacturing environment, it is termed a “complex” job shop scheduling problem as discussed by Mason, Fowler, and Carlyle (2000). Additional information about semiconductor manufacturing is presented by Uzsoy, Lee, and Martin-Vega (1992) .

3 SIMULATION MODELS

Mason, Jensen, and Fowler (1996) conducted a benchmark study of simulation packages used in the semiconductor industry. The researchers found that discrepancies in the output results existed between replications of the same model in different simulation packages. While these differences were attributed in part due to the batching logic of the simulation packages under study, enormous improvements in these packages over the last five years has led to very comparable modeling capabilities amongst the available packages in terms of core simulation and semiconductor wafer fab modeling functionality.

Factory Explorer™ v. 2.7 was selected for the simulation models of the production line because of its use in the semiconductor industry, its convenient interface, and resulting fast adoption time. The software package is a dynamic simulation package allowing models to represent system changes over time. Factory Explorer™ is distributed by Wright, Williams and Kelly `<http://www.wwk.com>`.

The Factory Explorer™ interface uses several Microsoft Excel worksheets, which provide information about the tool groups, area operators, product process steps, and the volume and types of products to be manufactured. As Brown *et al.* (1997) state, models may be developed quickly in Factory Explorer™ by importing the Excel™ files. With the software’s orientation to the semiconductor industry, the computer run times are quick for most models allowing for multiple runs to be made for given scenario under study.

3.1 Experimental Data

In this experiment, two products, Product 1 and Product 2, will be manufactured together. Three levels of demand are considered, each across a five year horizon; these levels are referred to as weak, average, and strong demand. The production levels in wafers for each product are presented in Table 1. For each demand level and year, the top (bottom) number is the planned production level in wafers for Product 1 (Product 2). In the data, it may be seen that the product mix shifts from Product 1 towards Product 2 during the five year horizon.

Table 1: Test Bed Dataset

	Year1	**Year2**	**Year3**	**Year4**	**Year5**
Weak	18406	17762	11749	2727	0
	0	772	8271	19608	22994
Average	33110	30900	21737	14695	14703
	4588	7342	18841	27573	27582
Strong	36760	30912	21482	7722	0
	52	7358	19162	36339	45937

The proposed wafer fab is divided into seven tool areas and is comprised by a total of 25 different types of machines. Initially, one operator is assigned to each tool area, and one maintenance operator is hired to service the entire pilot line's tool repairs. It is assumed that one of each machine is initially purchased by the company. We will assess additional tooling and operator requirements through our simulation model.

3.2 Limitations and Assumptions

In constructing the model, it is assumed that no setup times exist in the process. Processing times for all operations are uniformly distributed (+/- 10%) to allow for the expected variability in our pilot line process. The release rate of wafers into the pilot line is equally distributed throughout the production year on a weekly basis.

We assume that the mean time between failures (MTBF) for pilot line equipment can be characterized by an exponential distribution. Furthermore, the maximum capacity loading for all tools is set to 84% to prevent overloading the machines. This maximum loading value represents an industry average value for balancing WIP levels with equipment costs. Once a tool's capacity loading exceeds this level, an additional tool will be purchased.

Finally, we assume that operators are compensated at a rate of $16 per hour, with an additional 35% of pay required to cover their fringe benefits. All shifts were assumed to be eight hours, with three shifts possible per day.

3.3 Verification and Validation

In the design of a pilot production line, the possibility to test the model against factual data does not exist. It was determined analytically that several machines were likely to be constraining resources, as our model identified these machines as bottlenecks. Also, the results from simulations were "sanity checked" and it was determined that cycle times and WIP levels were within expected levels for base model scenarios.

Initialization bias was not considered because of the nature of the problem. In this case, the plant itself can expect to undergo delays and extremes in cycles times, because neither the plant nor the model are initially populated with jobs. Hence, we are not initially studying steady-state production capacity; but instead, production start-up/ramp-up capabilities. For each experimental case, 20 simulation replications were performed to assess the expected performance of the pilot production line.

4 RESULTS

The results of the simulation experiments are presented in three groups based on the demand level: weak demand, average demand, and strong demand. Presented first in each section is a table indicating the tooling requirements for the demand scenario by the number of shifts operated. While one, two and three-shift options were tested and evaluated, the one-shift option performed quite poorly in terms of cost feasibility for base model scenarios. Therefore, the decision was made to discontinue our investigations into this case. Only those tool and area operators with non-unit quantities are presented in the results tables.

After the tooling requirements, a discussion follows of the associated costs, estimated work-in-process levels, and estimated cycle times for each demand scenario. WIP levels are important in semiconductor manufacturing because of the high cost associated with each individual wafer. At a thousand dollars or more apiece, wafer inventories can quickly escalate into the millions of dollars. Cycle times are also important due to the criticality of delivering products in a timely manner. It should be noted that although the results presented may differ in cycle times and WIP levels, consistent throughput levels were maintained in all models to provide for more valid comparisons.

4.1 Weak Demand Scenario

The weak demand scenario represents a situation whereby the products produced are not readily adopted for use. The weak demand scenario of course requires the least number of operators and tools of any scenario. Table 2 shows the tooling and operator requirements for the pilot line given weak demand and the option of running three shifts or reducing production to only two shifts pre day.

Table 2: Staffing Requirements for Weak Demand

Three Shifts					
Tool / Operator	*Yr1*	*Yr2*	*Yr3*	*Yr4*	*Yr5*
Maintenance Op.	3	3	3	3	3
Two Shifts					
Tool / Operator	*Yr1*	*Yr2*	*Yr3*	*Yr4*	*Yr5*
Area 7 Operator	1	1	1	2	2
Maintenance Op.	4	4	4	4	4
Testing Device	2	2	2	2	2

Table 2 indicates that the maintenance operators are the highest demand operators under both shift scheduling scenarios. Under the weak demand scenario, the primary staffing consideration is to provide enough maintenance workers to keep the machines operating (three operators with three shifts, four operators with only two shifts). It may also be seen that as the product mix changes, Area 7 demands more operators to maintain production levels. This is because several tools primarily used by Product 2 are assigned to tool area 7. The only tool type that requires additional machines is the testing device under the two-shift production option.

Cost differences exist between the shift options because of the differences between staffing and equipment levels. The two-shift production option showed a 7% increase in investment costs due to the extra testing device. However, the operating costs decreased by 23% in favor of the two-shift option. The overall difference between total costs through the fifth year of production is 20% in favor of the two-shift option.

Work-in-process levels increased by a factor of three for the two-shift option (changed from 300 to 900 wafers). With the increased work-in-process levels, a corresponding increase in lot cycle times is expected. Figure 1 indicates the average cycle times per product for both the three-shift and two-shift production options.

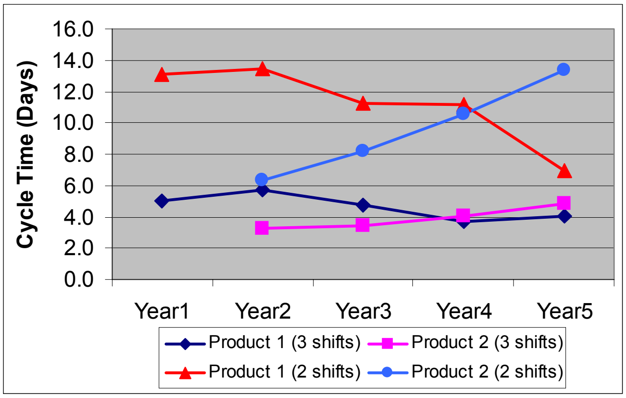

Figure 1: Cycle Times with Weak Demand

Figure 1 shows that the cycle times of both Product 1 and Product 2 remain fairly steady under the three-shift option (ranging from 3.4 to 5.1 days for Product 1 and from 3.2 to 4.8 days for Product 2). Under the two-shift option, cycle times are considerably higher, but are still within acceptable levels. The cycle times are however much less steady and tend to vary with product mix changes.

4.2 Average Demand Scenario

The average demand scenario sees an increase in annual production levels from the weak demand scenario. As demand and production requirements increase, so do the tooling and staffing requirements. Table 3 indicates the tool and operator staffing requirements for the three- and two-shift production options. Shown here is that the maintenance operators continue to be in high demand, primarily because of the "cost" of downtime. Also, the testers are increased due to increased demand in general.

Area 7 operates several tools which primarily process type 2 products. Among these tools is the press. Therefore, as the number of wafers of Product 2 increases each year, the demand on Area 7 also increases. The results in the necessity of adding an operator in both scenarios and adding the press in year four of the two-shift option.

Table 3: Staffing Requirements for Average Demand

Three Shifts					
Tool / Operator	*Yr1*	*Yr2*	*Yr3*	*Yr4*	*Yr5*
Area 7 Operator	1	1	1	2	2
Maintenance Op.	3	3	3	3	3
Testing Device	2	2	2	2	2
Two Shifts					
Tool / Operator	*Yr1*	*Yr2*	*Yr3*	*Yr4*	*Yr5*
Area 7 Operator	1	1	2	2	2
Maintenance Op.	5	5	5	5	5
Press Device	1	1	1	2	2
Testing Device	3	3	3	3	3

The cost effects of the tooling and staffing requirements were proportionally equivalent to the weak demand case. The two-shift production option was therefore the more cost effective option, saving approximately 14% over five years.

Work-in-process levels did increase considerably for both manufacturing options, but more dramatically for the two-shift option. WIP levels for the two-shift option were between two and three-thousand wafers as compared to six to seven hundred when manufacturing with three shifts, a factor of over four.

Cycle times for the two-shift option correspondingly increased with the higher WIP levels. Cycle times based on three shifts of production were only slightly higher than under the weak demand scenario and continued to be more robust to product mix changes. The cycle times are presented in Figure 2.

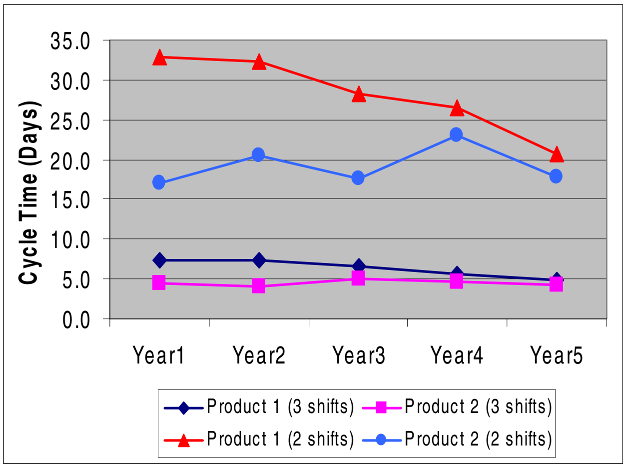

Figure 2: Cycle Times with Average Demand

Under the two-shift production scenario, a drop in average cycle times is noticed. This is attributed to the change in process steps. As the volume of Product 2 increases in the product mix, some tools used primarily by

Product 1 have eased constraints while other machines, which primarily process Product 2, inherit the difference.

4.3 Strong Demand Scenario

The strong demand scenario is the most optimistic of the planning contingencies and requires the highest levels of staffing and tooling. Table 4 presents the fab requirements assuming strong demand.

Table 4: Staffing Requirements for Strong Demand

Three Shifts					
Tool / Operator	*Yr1*	*Yr2*	*Yr3*	*Yr4*	*Yr5*
Area 7 Operator	1	1	1	2	2
Maintenance Op.	3	3	3	3	3
Press Device	1	1	1	1	2
Testing Device	2	2	2	2	2
Two Shifts					
Tool / Operator	*Yr1*	*Yr2*	*Yr3*	*Yr4*	*Yr5*
Area 7 Operator	1	1	2	2	3
Maintenance Op.	4	4	4	4	5
Dispense	1	1	1	1	2
Pick & Place	1	1	1	1	2
Press Device	1	1	1	2	2
Screenprint Via Fill	1	1	1	1	2
Testing Device	3	3	3	3	2

The table indicates the same trends as previously mentioned. Area 7 operators once again increase towards the end of the five-year horizon because of the Product 2 increase. The "dispense", "pick & place", and "press" tools are all assigned to Area 7 and are primarily Product 2 service machines. The increased maintenance worker in year five of the two-shift option is a result of the increased number of machines in that same period.

Equipment savings on the three-shift option are approximately 28% over the two-shift option. The operating cost savings though, is approximately 15% in favor of the two-shift option. The end result is that a 9% saving may be obtained over the five-year horizon with the two-shift option. Furthermore, unit costs for the two-shift option are consistent lower by up to 30% per piece.

While direct cost issues favor the two-shift option, this option suffers from considerably higher and more variable cycle times. It may be seen in Figure 3 that the cycle times spike at an average of 33 days for product 1 under the two-shift option. Mean while, the three-shift method never sees more than an eight day cycle time.

With considerably higher cycle times, it is expected that WIP levels are also higher for the two-shift option. Indeed, expected WIP levels were again much higher for the two-shift option by a factor of three to five times the three-shift level.

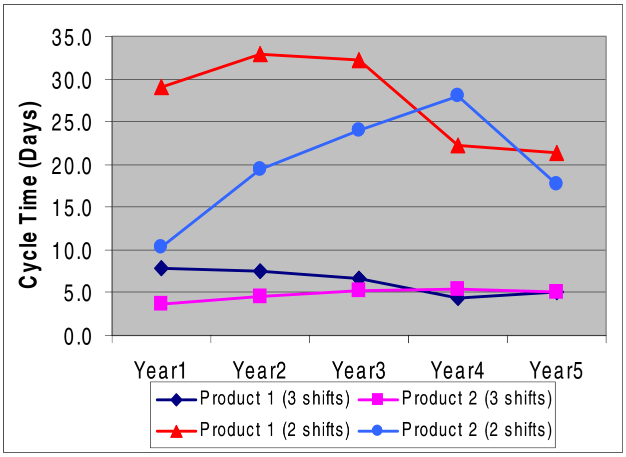

Figure 3: Cycle times with Strong Demand

5 CONCLUSIONS

The semiconductor industry is rapidly expanding worldwide. With the continuing advancement of technology, companies are continually striving to develop and maintain cutting edge products to stay "ahead of the curve." We presented a case study example of how simulation can be used to establish the initial tooling and operator requirements for pilot production lines, as well as to estimate the fixed and recurring costs associated with the line.

The simulation models indicate two primary results. First, with the assumed costs used in the project, it was always more cost efficient to manufacture under a two-shift production plan than a three-shift production plan. The percentage of total savings over five years ranged from nine to 20% depending on the demand for products. However, this value consistently decreases as production levels increase. Second, while direct costs were lower for the two-shift production option, work-in-process levels and lot cycle times were increased by a factor of three or more.

Justification for the cost effectiveness of the two-shift plan is most likely because no costs associated with work-in-process levels was taken into account. It is well known that with each wafer worth thousands of dollars, high WIP levels may severely impact the overall economic performance of a company, and thus should be taken into account in real world applications of simulation modeling. Further, cost per good unit out of the factory needs to be considered explicitly, as while total dollars are important, unit costs drive profit calculations and should be considered in future analyses of the pilot production line.

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