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Title: Modeling an Integrated Circuit Wafer Fabrication Line: Investigation of the Relationship Between Batch Size and Overall Cycle Time

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Abstract: These authors investigated the relationship between batch size and entry rate at which new materials are added to the factory floor and their affects on work-in-progress (WIP) levels, cycle time, and annual margins. One method for carrying out such an investigation in any process-based line is presented.

Modeling an Integrated Circuit Wafer Fabrication Line

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MODELING AN INTEGRATED CIRCUIT WAFER FABRICATION LINE:

Investigation of the Relationship Between Batch Size and Overall Cycle Time

Good project (A)

Engineering Management 506
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EXECUTIVE SUMMARY

Batch size and the rate at which new material is added to the factory floor can be balanced in such a way as to optimize cycle time, work-in-process (WIP) inventory, and annual margins. By collecting machine operating data and carrying out an analysis, significant gains can be made in the operation and profitability of a process based manufacturing line. Discrete system simulation assists the analyst in carrying out the analysis of a complex manufacturing system by allowing the analysis to account for the dynamic interaction of many variables.

In this case, an integrated circuit wafer fabrication line was modeled. Process based manufacturing presents challenges atypical of assembly type operations due to complex interactions between batch size, set-up time, and losses due to process yields.

The relationships between batch size and entry rate, and their affects on WIP levels, cycle time, and annual margins is investigated in this paper and a method for carrying out such an investigation in any process based line is presented.

Based on observation of the results, some rules of thumb were developed:

- The cost of processing per wafer drops quickly, at first, as batch size increases.
- Cycle time increases, for a given batch size, as the "feed" rate of new material increases.
- Once a machine's processing rate has been exceeded by the feed rate, both cycle time and WIP begin to climb dramatically.
- Cycle time is sensitive to changes in batch size, at a given a feed rate.
- By looking at the behavior of WIP and cycle time with respect to feed rates, a feed rate can be chosen that provides low levels of both and does not exceed the bottleneck rate of a machine.

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MODELING AN INTEGRATED CIRCUIT WAFER FABRICATION LINE:

Investigation of the Relationship Between Batch Size and Overall Cycle Time

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I. INTRODUCTION

Reason for the Analysis

Manufacturing operations that are primarily dependent upon chemical processing present special challenges over and above the traditional problems encountered in an assembly based manufacturing line. Process based manufacturing leads to engineering and management issues that are unique to this type of industry:

- RELATIVELY UNSTABLE - The processing equipment is notoriously sensitive and unreliable. The processes themselves are quick to change due to small, and possibly difficult to detect, changes in the equipment or environment. Processing yields fluctuate and sudden losses of material make it difficult to carry out a production plan that is meaningful for very long.

- TECHNICAL STAFF - The instability and complexity of the processes results in the need for a relatively high proportion of highly trained technicians and engineers, who do not directly produce products, to develop and sustain operations. Significant training of up to six months is necessary before production operators become effective contributors. These two factors result in relatively high "indirect" labor costs and a difficult to build "direct" labor force.

- CAPITAL INTENSIVE - In order to control processing as much as possible, the equipment is comprised of complex controls components. It may employ technologies such as high voltage, high temperature, highly corrosive and toxic substances, high pressure, or high vacuum. Naturally, this sort of equipment is very expensive and leads to a very capital intensive business.

- HIGH FIXED COSTS - All of this complex equipment and exotic processing typically requires a specialized facility in which processing can be successfully carried out. Very tight specifications regarding temperature, humidity, airborne particulate, and ultra pure process reagents may be required. Toxic and hazardous waste needs to be disposed of in an environmentally responsible manner. These requirements lead to costs that are largely independent of the level of plant output.

In order to be competitive in any industry, the issues of manufacturing cost structure and the ability to be responsive to the market's needs are crucial. In process based manufacturing, the characteristically high overhead of equipment and facility costs, coupled with the relatively large proportion of indirect staff, make the cost structure difficult to understand and control. The complexity and instability of the production line makes cycle time reduction difficult and slows the implementation of manufacturing changes for process improvement or new products. Sudden losses of entire batches of material seem to make "production planning" an oxymoron.

The interrelationships between processing losses, costs, and the availability of trained people make this a difficult system to optimize.

Scope of the Analysis

Our goal is to further the body of knowledge regarding strategies available for improvement in process based manufacturing operations. Specifically, we have chosen to study the effects of changes in batch size on operating costs and cycle time. This investigation was undertaken because we suspect that the cash investment made in work in process inventory (WIP) can be optimized by appropriately adjusting this variable. We also expect, that by optimizing the batch size, significant gains in the elapsed time material spends in the line (cycle time) will be produced.

Integrated circuit (IC) manufacturing contains each of the processing industry challenges mentioned above. Due to our particular interest in this industry, we have selected it as the "test vehicle". In particular, we have modeled the wafer fabrication portion of an IC manufacturing line. We expect the results of our work to be of interest to manufacturing managers and process engineering managers.

The premise for our study revolves primarily around two relationships that seem to push management of the line in opposite directions:

1. In order to maximize equipment, labor, utility, and other resource utilization, batch sizes ought to be large enough to fill each machine to capacity before it is operated.
2. Full machine loads of a large batch, expose the entire batch to the risk of processing failure all at one time. The subsequent loss of entire batches may lead to potentially late shipments to customers and, in general, long cycle times between batch initiation and shipment of finished

product. In addition, for some machines that have smaller processing batch sizes, a large batch will wait a long time before being passed on. This type of phenomenon has the effect of increasing the overall WIP, tying up additional working capital and lengthening the cycle time.

An issue related to cycle time is processing equipment availability. Manufacturing may be interrupted due to equipment failure or loss of process control. Correcting the failures requires technicians and engineers to trouble shoot and repair the equipment. Not included in this study is an analysis of the effect on cycle time of varying the number of available technicians. The model we developed is designed to allow study of determining the effects on operations of varying the number of maintenance technicians available. However, in order to avoid confounding the results of our study regarding batch size, the number of technicians available was considered unlimited. Further investigation regarding the effects of restricting the number of maintenance technicians could be undertaken at a later date without additional changes to the model.

Our intent is to provide a model that can be used to determine the most effective batch size and technical staffing strategy towards minimizing overall cycle time (including the effects of losses due to equipment failure). A byproduct of using this model will be a better understanding of the product cost structure of this type of industry. The advantage of this sort of computer model is that as specific parameters change over time, the model can be adjusted and re-run to yield results based on the up-to-date data.

II. MODELING of the WAFER FABRICATION AREA

The Modeling Approach

In order to address the primary issues under investigation, it is unnecessary to model the entire manufacturing line. Therefore, although we collected data on the entire line (Appendix B) for the sake of becoming familiar with our subject, we have chosen to model only a portion of the line. We have chosen a subset of processes to model so that the key issues of process failure and equipment usage for multiple process steps are addressed (Appendix C).

Selection of the Modeling Tool

To build the model, we chose to use a discrete system simulation software product. This product allowed us to build a detailed computer based model of an existing wafer fabrication line including:

- Product routing through each machine.
- Processing times and yields at each step.
- Equipment and process failure rates.
- Labor requirements for processing and maintenance.
- Processing costs for labor, materials, and utilities.

We have been able to validate simulated results against actual results from the existing line before experimenting with different batch sizes and the number of maintenance technicians.

For the sake of portability and convenience, we chose a discrete system simulation product that used an IBM compatible 386 personal computer (PC) platform running under Microsoft Windows 3.1. Tabulation of modeling data and preliminary analysis were carried out using a spreadsheet also running under Microsoft Windows 3.1.

Modeling the Manufacturing Line

Formulation of the Model

In order to create the model, data regarding each processing step needed to be collected. For each step we needed to understand and collect operating characteristics such as:

- Processing time.
- Minimum and maximum batch size.
- Time a person must be present and time a person is free to do other tasks simultaneously.
- Details of the route taken by batches, process by process, through the factory.
- Equipment set up time at each process step per batch.
- Equipment used for each process.
- Process yield and machine or process failure rate for each process.

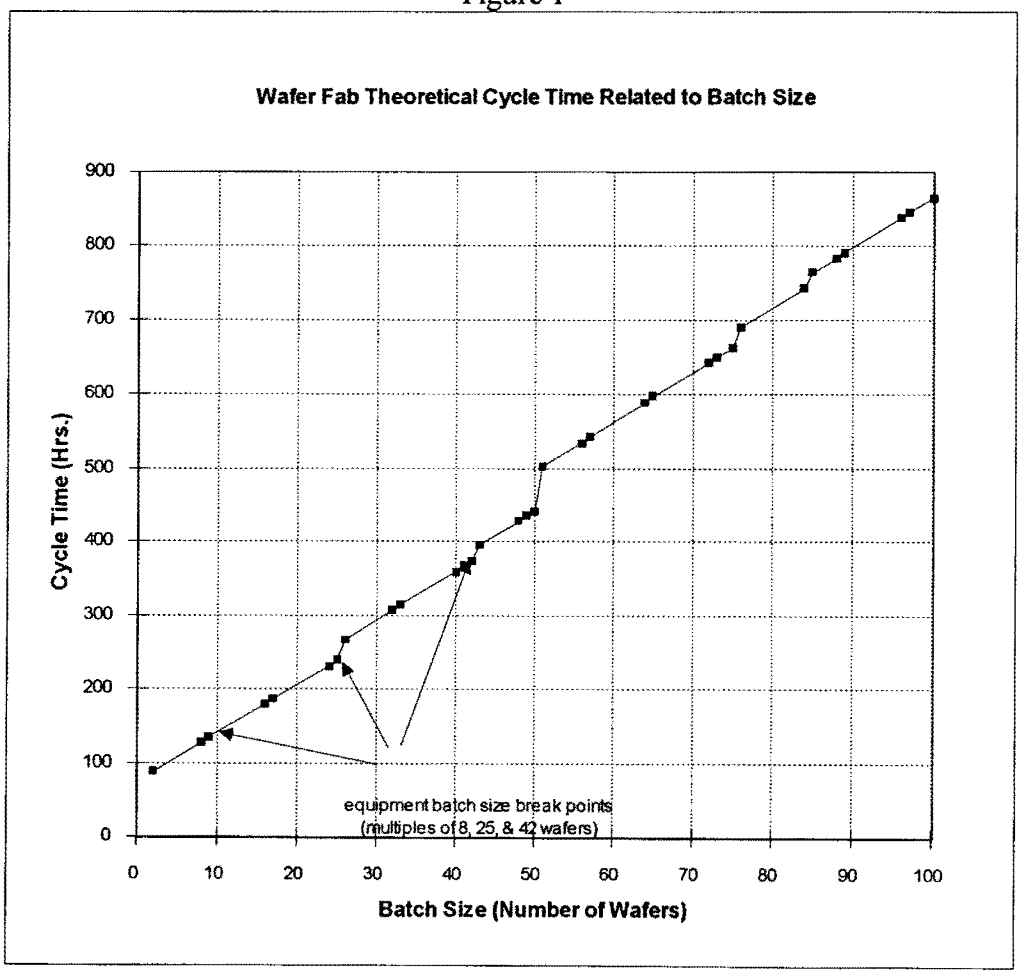
Appendix A contains the list of equipment used and its related failure and cost data. Appendix B contains the routing and processing data for the entire fabrication line, a portion of which we have modeled (Appendix C).

The Initial Ideal Model

The first step we took was to produce a spreadsheet based model using "ideal" conditions. This model (Appendix C) computes the theoretical minimum cycle time under static factory conditions assuming that batches of material are continuously processed without ever waiting. This analysis provided us with some fundamental understanding of the system we were about to model using the simulation product.

Figure 1 displays the relationship between batch size and minimum cycle time. Notice that as batch size increases, cycle time increases in a linear manner with some discontinuous points.

Figure 1



Appendix D contains a table showing the total time, required by each machine modeled, to process a batch of product for various batch sizes. The time for a machine to process a batch of material includes the set-up time plus the per wafer time.

The discontinuities result from maximum batch sizes being reached and then exceeded in batch oriented machines. Each of these machines has a characteristic batch size. Regardless of how many wafers are to be run, the machine will take the same amount of time, up to the point where it is processing a batch equivalent to its full capacity. Once this capacity has been reached, another entire machine cycle is required to complete processing of the batch.

The underlying slope is due to the fact that some machines have a characteristic processing time per wafer. That is, their batch size is one. It is these time-per-wafer elements, summed over all machines, that determine the slope of the line.

The computations for the data in Figure 1 are shown for a batch size of 25 wafers in Appendix C and summarized with total processing times shown for several batch sizes in Appendix D.

Figures 2 and 3 below show how the maximum processing rate for various machines varies with respect to batch size. Figure 2 illustrates those machines that have a batch size of 1 wafer with a characteristic set-up time for a batch of wafers regardless of size. As can be seen, after the wafers per batch grows, the set-up time is amortized over a greater number of wafers so the net time per wafer tends quickly towards the actual time per wafer, making set-up time irrelevant.

Processing Rates and Batch Sizes

Figure 2

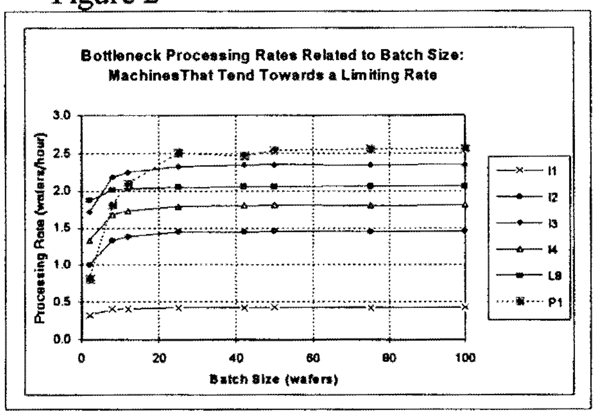


Figure 3

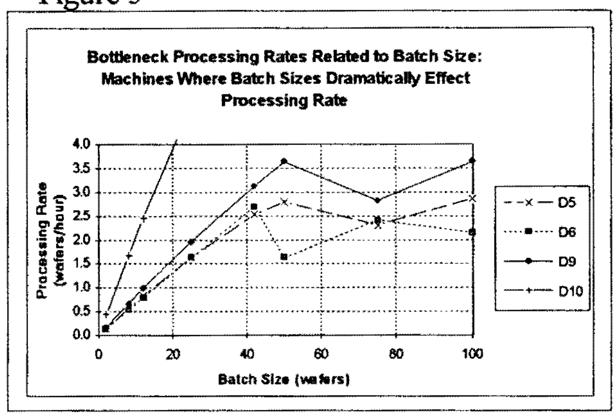


Figure 3 shows how processing time per batch can vary wildly when a machine has a large maximum batch size. The machines shown here have a batch size on the order of 40 to 50 wafers. This makes the processing rate per wafer drop significantly once a batch break point is reached. For example, if a machine had a batch size of 50 wafers, but the batch to be processed was 51 wafers, it would take two processing runs to complete processing for the batch instead of just one run for a 50 wafer batch.

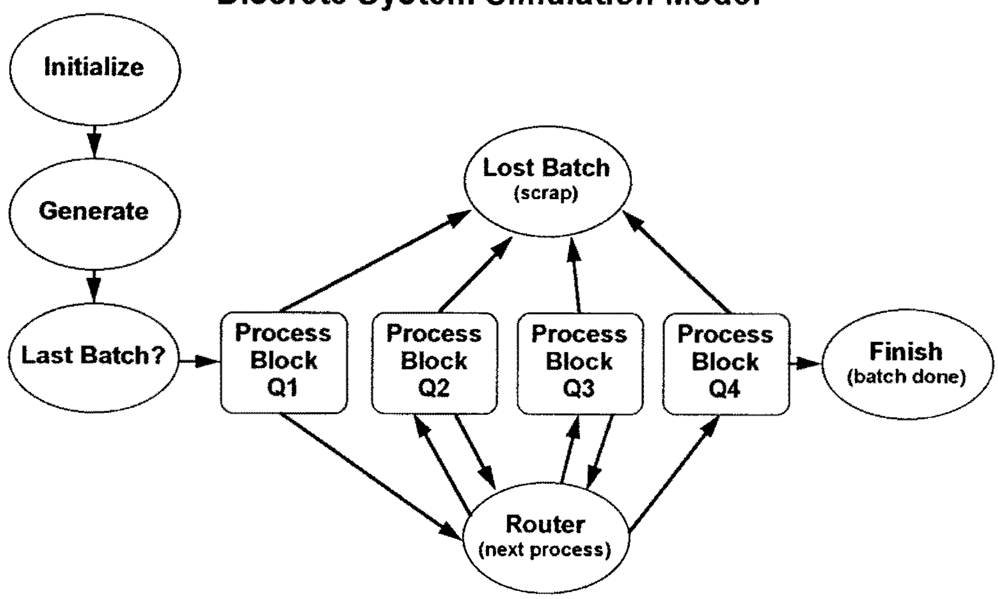
The first simulation model we constructed did not take into account such factors as process or equipment failure. In this way we were able to verify that material movement, routing, and cycle time were comparable to actual working conditions and consistent with the ideal conditions shown by the spreadsheet model.

Figure 4 contains a graphical representation of the simulation model. It depicts the process flow we have chosen to model. The equipment used and routing of material are shown at an over view level. Actual detailed flow routing is embedded in the graphical elements of the simulation screen on the computer. Our model includes roughly the first 40% of the line. However, it is characteristic of the typical wafer fabrication processing line. It includes such features as:

- Some equipment being used multiple times for successive but not adjacent processing steps.
- One person is able to operate more than one process simultaneously.
- Some processes require single wafer processing, others are capable of large batch processing.

Figure 4

Schematic Diagram of the Discrete System Simulation Model



The processing steps required to produce completed wafers have been grouped such that each device structure is completed when all of the processes within a block are completed. Each block requires the use of several machines in a prescribed sequence. Each machine may be used for several non-consecutive process steps and for steps within different blocks.

Since the wafers are relatively small and light, the space and transportation issues commonly encountered in manufacturing systems are not factors in this case. Many days of material can be stored and moved easily by one person on a cart. This simplifies the model, and in fact to some degree simplifies some of the material handling issues in designing a wafer fabrication facility. Although not a factor in this model, the primary concerns regarding material handling revolve around keeping the material clean and dry. The manufacturing environment is temperature and humidity controlled. In addition, the air is highly filtered to remove airborne particulate. Special consideration is given to anything (or any body) brought into the cleanroom to prevent particulate from being shed into the manufacturing environment.

Extending the Model

Once the model was verified for accuracy under ideal conditions, the additional attributes regarding machine failure and repair rates were added. Modeling choices were made regarding the circumstances under which batches of material would be scrapped.

In the actual manufacturing line, losses are almost always in quantities related to a machine's batch size. Individual wafers are rarely lost. To simplify the model we assumed that individual wafers are never lost, only groups of wafers in process simultaneously are lost due to machine or process failure. In the model, as in the production line, machine failure does not necessarily lead to loss of product. Interruption to product flow may occur, losing only machine hours, without scrapping material. A partial listing of the model that was constructed is included in Appendix E.

<u>Selection of Test Variables</u>

The finished model allows for changing particular variables of interest. For instance, we are able to set the batch size and the time between releases of wafer lots entering the line. A batch is not allowed to move on to the successive step until all of its wafers have been processed at its current step. We are interested in the relationship between batch size and cycle time through the line.

The other relationship we were interested in studying is how the number of available technicians effects the elapsed time to repair a machine or process and therefore the effect on overall batch cycle time. The model has been designed to accommodate this study, but we chose to concentrate only on the effects of batch time and rate of wafer entry into the factory for this project.

So, in each case the dependent variables of interest were cycle time, WIP levels, and product costs. Our approach to collecting data from the model is shown in Table 1.

Batch Size	Entry Rate
Varied from 2 to 50 wafers	Varied from .067 to 1.2 wafers/hour

Table 1 - Sequence Used to Study Dependent Variables

For each of the simulation runs, a single product type was assumed to run through this line. The model provides for the possibility of five different products that differ only in that they run through a different route using a different combination of processes. Processing times and yields are the same at a given step for all products. We used only one product to enable us to clearly understand the behavioral relationship between batch size and entry rate with respect to cost, cycle time and WIP levels.

Data Produced by the Model

During a simulation run statistics are accumulated, for other interesting manufacturing line characteristics, such as waiting time for each lot at each step, machine time for each lot at each step, total product scrap, total WIP, and queue length at each machine. An example of the output files produced by the model is shown in Appendix F. Each simulation was run for a sufficient amount of product (500 wafers) so that a steady state condition was reached. No constraints were placed on queue lengths, the number of operators, maintenance personnel, or total WIP.

As a result of accumulating pertinent statistics, conclusions can be drawn regarding product manufacturing costs, manufacturing line bottle-necks (as evidenced by ever lengthening queues), and overall machine utilization rates. The following section explores the relationships between the independent variables of batch size and entry rate, and the dependent variables of WIP, cycle time, cost per wafer, and machine utilization.

III. ANALYSIS of MODEL GENERATED DATA

Model Validation

By examining actual manufacturing records, and reviewing the simulation model's results with managers and engineers, we were able to complete validation. In addition, the simulation results compared very well with the static condition analysis. Actual and modeled data are in substantial agreement. Based on this we are able to draw reliable conclusions from the experiments we carried out using the model.

Explanation of Analysis Technique

As previously mentioned, an analysis of the ideal static condition of the production line was carried out using a spreadsheet. This analysis pointed out which machines we would expect to become bottlenecks in the line, given combinations of batch size and times between entry of batches. A table of Hours-Between-Entry was created for various "feed" rates of new material into the line (Appendix G). This table specified feed rates according to when we expected to see equipment bottlenecks (review Figures 2 & 3 for expected bottleneck rates). Appendix D contains a table detailing the maximum processing rates (bottleneck rates) possible for each machine given a variety of batch sizes.

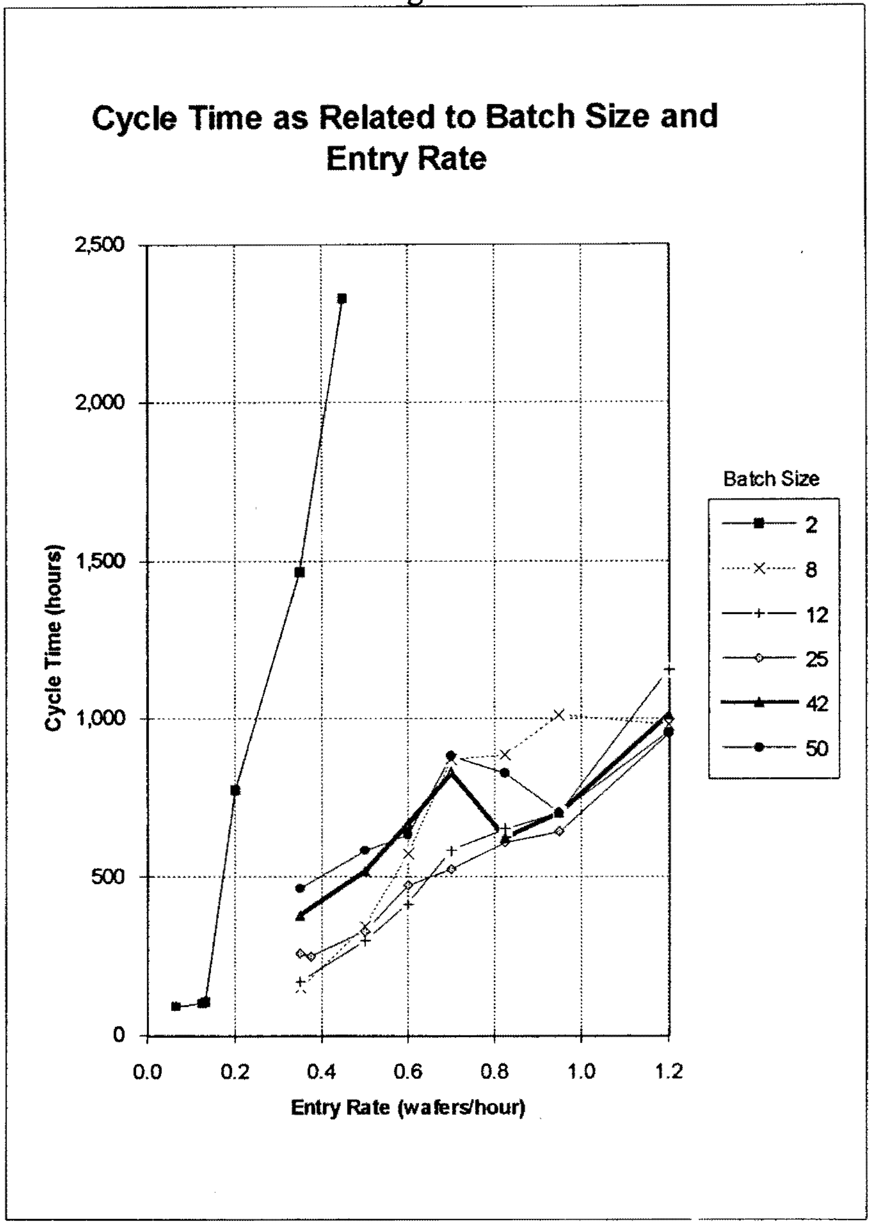
Using the table of Hours-Between-Entry we proceeded with running the simulation model using feed rates approaching and reaching bottleneck rates for various batch sizes. Each simulation run produced three files of results (see Appendix F for an example). This raw data was imported into a spreadsheet to facilitate analysis.

The spreadsheet allowed graphing and understanding of the various relationships.

IV. OBSERVATIONS FROM the DATA

Batch Size and Cycle Time

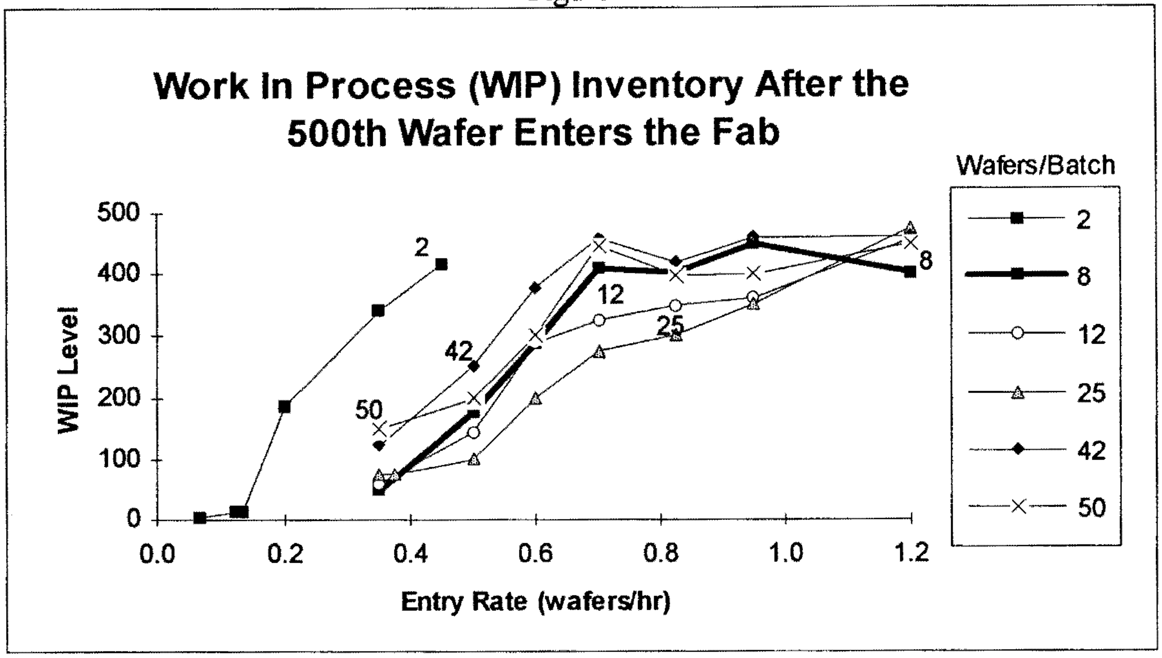
Figure 5



Clearly, cycle time is sensitive to both the entry rate of new material into the factory and the batch size chosen. We expected that cycle time for each batch size would increase from the theoretical minimum shown in Figure 1 (and shown above on the left end of each line) as material needed to wait for available machines due to the feed rate exceeding the processing rate. This did indeed occur. Not well understood is the phenomenon shown above where cycle time actually drops when very high feed rates were used. Nonetheless, the overall trend of increasing cycle time, and a quantification of this trend, were identified.

Batch Size and WIP Levels.

Figure 6



In an effort to effectively compare the WIP levels across simulations of various batch sizes, we had the simulation model take a snap-shot of WIP when the 500th wafer entered the factory. The simulation model continued to run until all 500 wafers were processed. In this way other per wafer or per batch related data could be collected without affecting our ability to compare WIP levels between runs of various batch sizes.

Batch Size and Product Cost

Relative processing costs were developed by studying the various types of costs incurred during wafer processing. It turns out that by far the largest portions of cost are facility, machine and utility related. In addition to these costs being large, they are fairly independent of how many parts are processed. It turns out that a reasonable approximation of relative cost to operate one machine compared to another can be developed by assessing the relative amount of floor space one machine occupies compared to another. This measurement of "foot print" and computation of relative occupied space was carried out and is shown in Appendix A. These relative costs were used in the simulation model so that proprietary cost data were not revealed.

We were not sure about the role entry rate would have on the cost to process wafers. Figure 7 display the relationship yielded by the model.

Figure 7

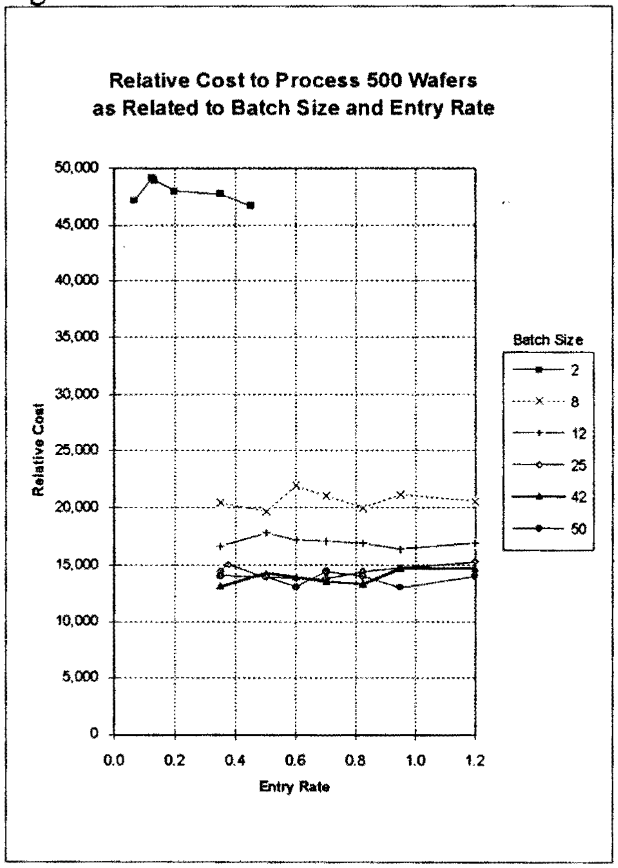
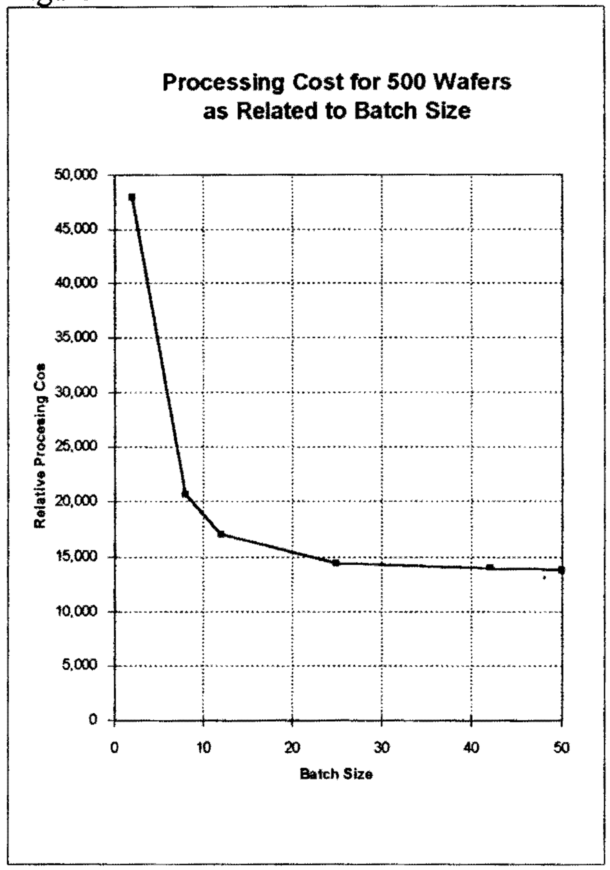


Figure 8



As can be seen above, product cost is fairly insensitive to changes in entry rate. Figure 8 more clearly demonstrates the effects of batch size on product cost (regardless of entry rate).

In the context of this analysis, product cost pertains to direct process related costs, not such overhead costs as marketing, product engineering, administration, etc.

Batch Size and Scrap Rates and Costs

Figure 9

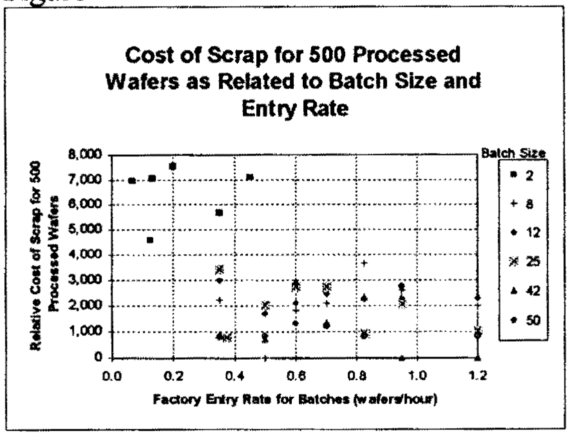
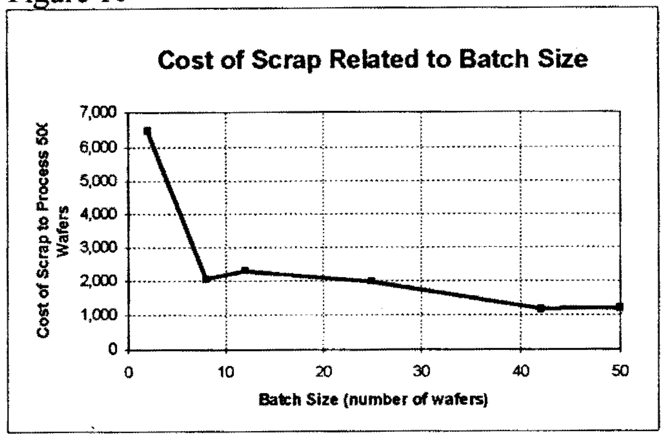


Figure 10



Again, the entry rate of new material into the factory appears to not have an affect on the amount of scrap or the cost it represents. This was a surprise to us. We believed that by reducing the batch size, the risk of losing large quantities of material due to machine failure would be reduced. This did not turn out to be the case.

V. CONCLUSIONS

Based on observation of the results, some rules of thumb can be summarized:

- The cost of processing per wafer drops quickly, at first, as batch size increases. This is largely due to the amortization of set-up costs over more wafers per batch. Clearly, as can be seen in Figure 8, most of the gain is made before the batch size gets very large. In this case, moving from 2 to 12 wafers per batch results in 90% of the potential drop in cost from 47,983 to 17,001 per 500 wafers. At large batch sizes the cost curve drops to around 13,800 .
- Cycle time increases, for a given batch size, as the "feed" rate of new material increases. This would tend to have us keep batch size small. This is related to the maximum processing rate that bottleneck machines can achieve.
- Once a machine's processing rate has been exceeded by the feed rate, both cycle time and WIP begin to climb dramatically.
- Cycle time is sensitive to changes in batch size, at a given a feed rate. This is a result of all wafers in a batch having to wait until processing is complete at this step before the whole batch moves to the next step.

- By looking at the behavior of WIP and cycle time with respect to feed rates, a feed rate can be chosen that provides low levels of both and does not exceed the bottleneck rate of a machine. In this case, machine I1 is the first bottleneck. (See Figure 3.)

Table 2 below shows the calculations for the cost of producing a year's worth of maximum level output from the factory as modeled. In order to compute the maximum cost and revenue, a "turns ratio" must be calculated. This is done by dividing the number of available work hours per year by the cycle time. This tells us the number of times the WIP can be turned in one year, thus yielding the maximum output level per year.

Table 2
Annualized Cost and Revenue Analysis
Assuming a Wafer Entry Rate of .35 wafers/hour

Batch Size	Processing Cost Avg/500	Processing Cost cost/wfr	WIP at Entry Rate .35 wfr/hr	Annual Cost of Money for WIP being tied up: wip value	Annual Cost of Money for WIP being tied up: i=20%	cycle time (hrs)	@2 sh/day @250dy/yr =turns/yr	Maximum Output wafers/yr	Total Processing cost/yr	Revenue/wfr 250 Total Rev/yr	Annual Factory Margin
2	47,983	95.97	340	32,629	6,526	1,467	2.7	927	95,520	231,839	136,318
8	20,682	41.36	48	1,985	397	151	26.5	1,271	52,974	317,766	264,792
12	17,001	34.00	60	2,040	408	173	23.1	1,389	47,624	347,157	299,533
25	14,480	28.96	75	2,172	434	261	15.3	1,151	33,771	287,786	254,016
42	14,007	28.01	124	3,474	695	382	10.5	1,297	37,040	324,356	287,317
50	13,850	27.70	150	4,155	831	464	8.6	1,292	36,634	323,116	286,482

Given a cost per wafer and a revenue per wafer, a simple gross margin can be computed to show which batch size will produce the highest margin (not necessarily the highest revenue). The right hand side of Table 2 above demonstrates this computation.

Figure 11

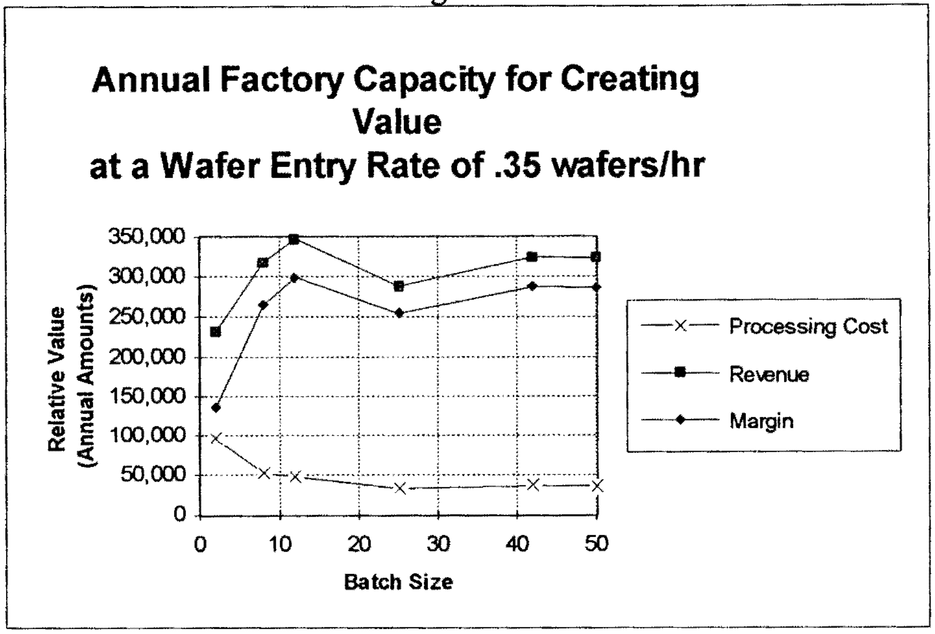


Figure 11 above, depicts the results of the margin analysis graphically.

Not only does the batch size of 12 wafers offer the highest annual revenue, but also, it offers a significant cycle time gain (up to 60% shorter) over larger batch sizes. This gain in cycle time assists the operation in several ways:

- New products and experiments can make it through line much quicker thus shortening the design cycle.
- Less time is required to "flush out" bad or old material.
- Lower WIP levels put smaller amounts of material at risk at a given point in time if there has been a processing problem.

Summary

Batch size and feed rate can be balanced in such a way to optimize cycle time, WIP, and annual margins. By collecting machine operating data and carrying out an analysis, significant gains can be made in the operation and profitability of a process based manufacturing line. Discrete system simulation assists the analyst in carrying out the analysis of a complex manufacturing system by allowing the analysis to account for the dynamic interaction of many variables.