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A PROFIT-BASED LOT-SIZING MODEL FOR THE N-JOB, M-MACHINE JOB SHOP: INCORPORATING QUALITY, CAPACITY, AND CYCLE TIME

by

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A DISSERTATION

IN

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DOCTOR OF PHILOSOPHY

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CHAPTER

ABSTRACT

Existing economic order quantity models base their calculations upon operations management principles established in the early 1900's. These principles focused primarily upon the control and reduction of the firm's variable costs. Total Quality Management has shifted this focus from costs and local optimization to quality and systems optimization. The marketplace also has changed. It has expanded from being primarily domestic into a globally competitive marketplace. In this new business environment, quality, market share, and profits must be primary elements in all of the firm's operating policies.

Recent operations management theories, such as Goldratt's (1980) Theory of Constraints, not only address these concerns but redefine how operations management should think about the production system. This research proposal evaluates the classical economic order quantity model and proposes a new model that addresses the lot sizing decision for shop floor operations. A profit maximizing (rather than a cost minimizing) perspective is taken. In this research, a theorized model is derived that considers cycle time and quality issues in addition to the traditional cost issues of production, holding and setup. To validate this model, empirical data and a simulation model are developed to parameterize and collaborate the findings of the theorized model.

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LIST OF ABBREVIATIONS

a = Expected percentage increase in price.

b = Scaling constant for production costs.

C_{ij} = Consumables cost rate for the i^{th} operation of the j^{th} product.

c = scaling constant for setup costs.

C_p, C_{pk} = Process capability indices.

D_j = Period demand for the j^{th} product.

E_j = Number of re-entrance flows into the i^{th} operation for the j^{th} product.

F = Overhead factor.

g = Location of the bottlenecking process step within the transformation process.

H_j = Overhead costs factor for the j^{th} product.

h_j = Number of operating hours in a day for the j^{th} product.

I_h = Inventory holding cost.

I_L = Inventory level.

K = Fixed portion of the overhead costs.

k = Number of product types.

L_{ij} = Labor rate for the i^{th} operation of the j^{th} product.

LSL = Lower specification limit.

M_j = Market price for the j^{th} product.

m_j = Raw material cost for the j^{th} product.

N_j = Number of operating days in the period for the j^{th} product.

n_j = Number of processing steps in the transformation cycle for the j^{th} product.

n_s = Number of sample datams taken.

O_c = the ordering cost per order.

P_j = Production costs for the j^{th} product

Q_j = Lot or batch size the j^{th} product.

q = Probability of the process going out of control.

R_j = Revenues for the j^{th} product.

r = Learning curve rate.

s = Expected number of total setups.

S_j = Setup costs for the j^{th} product.

T_j = Expected system output for the j^{th} product.

T_j' = Maximum expected system output for the j^{th} product.

TVC = Total variable cost.

USL = Upper specification limit.

W_j = Cycle time for the j^{th} product.

w = Portion of total product comprised of by the jth product.

X_i = The i^{th} datam in a sample.

$\bar{X}$ = Sample average, or mean.

x = Number of production units.

Y_j = Process yield rate or process quality for the j^{th} product. This variable is a measure of the failure costs of quality when represented as 1-Y.

y = Number of time periods.

z = Scaling constant for lot size effects in production costs.

σ = Standard deviation.

$\hat{\sigma}$ = Estimated standard deviation.

α = Adjustment scalar to the variable portion of holding cost.

β_j = Variable overhead cost scalar quality for the j^{th} product.

γ_{ij} = Value-added at the ith processing step for the j^{th} product.

η_{ij} = Average expected number of lots per production run at the i^{th} operation for the j^{th} product.

λ = Arrival rate, or cycle time.

$\lambda_j = \frac{Q_j}{\psi_{bj}}$ = The cycle time of the firm for the j^{th} product.

$\bar{\lambda}_j$ = The industry average cycle time for the j^{th} product,

μ = For capacity indices means process mean, for queuing formulas means service rate.

π = Production rate.

θ_j = Fixed portion of overhead costs for the j^{th} product.

ρ = Process utilization.

τ = Time.

τ_{pij} = Processing time of the j^{th} product at the i^{th} operation.

τ_{Sij} = Setup time of the j^{th} product at the i^{th} operation.

ξ_j = Contribution to net profits of the ith unit for the j^{th} product.

ψ_{ij} = Load capacity of the i^{th} operation for the j^{th} product.

CHAPTER 1

INTRODUCTION

1.1. Introduction

This research is about a very familiar production problem that has recently been the focus of much controversy. That problem is the question of lot sizing in a manufacturing or production environment, particularly in the flow/job shop environment that characterize wafer fabs in the semiconductor industry. The trend for the past several years, as a result of such movements as Just-in-Time (JIT) and cycle-time reduction (CTR), has been towards ever smaller lot sizes irrespective of what such classical models as the Economic Order Quantity (EOQ) and the Economic Production Quantity (EPQ) would prescribe. Because of these trends, those models have fallen into disrepute in manufacturing environments.

After World War II, management was primarily concerned with meeting the high levels of demand that existed in the marketplace (Umble and Srikanth, 1990). If a firm had a strong product design and modest production capabilities, there was a market for everything it could make. Because of this situation there was little interest in the time required to bring products to the marketplace and in the related concepts of agility and flexibility. There was also little focus on the quality of the product produced. As a result, decisions and the tools developed to support the decision-making process were based primarily upon cost reduction. Figure 1-1 illustrates currently perceived causal relationships between costs, process quality, cycle time, capacity, price, throughput, demand, and lot size. The causal relationships depicted in Figure 1-1 will be discussed further in the development of the proposed new models. The relationships shown in Figure 1-1 shall be developed more fully in the subsequent chapters of this thesis.

1.2. Problem Statement

Today, firms recognize that market share cannot be sustained solely by cost reduction. As competition in the global marketplace increases and the customer's demands for higher quality levels and shorter cycle times increase, management's decisions must focus upon revenue generation, quality, speed (time-to-market, cycle time, order fulfillment time, etc.), flexibility, and cost reduction. Buffa (1984) said that day-to-day operating decisions, such as lot sizing, have major strategic implications for the

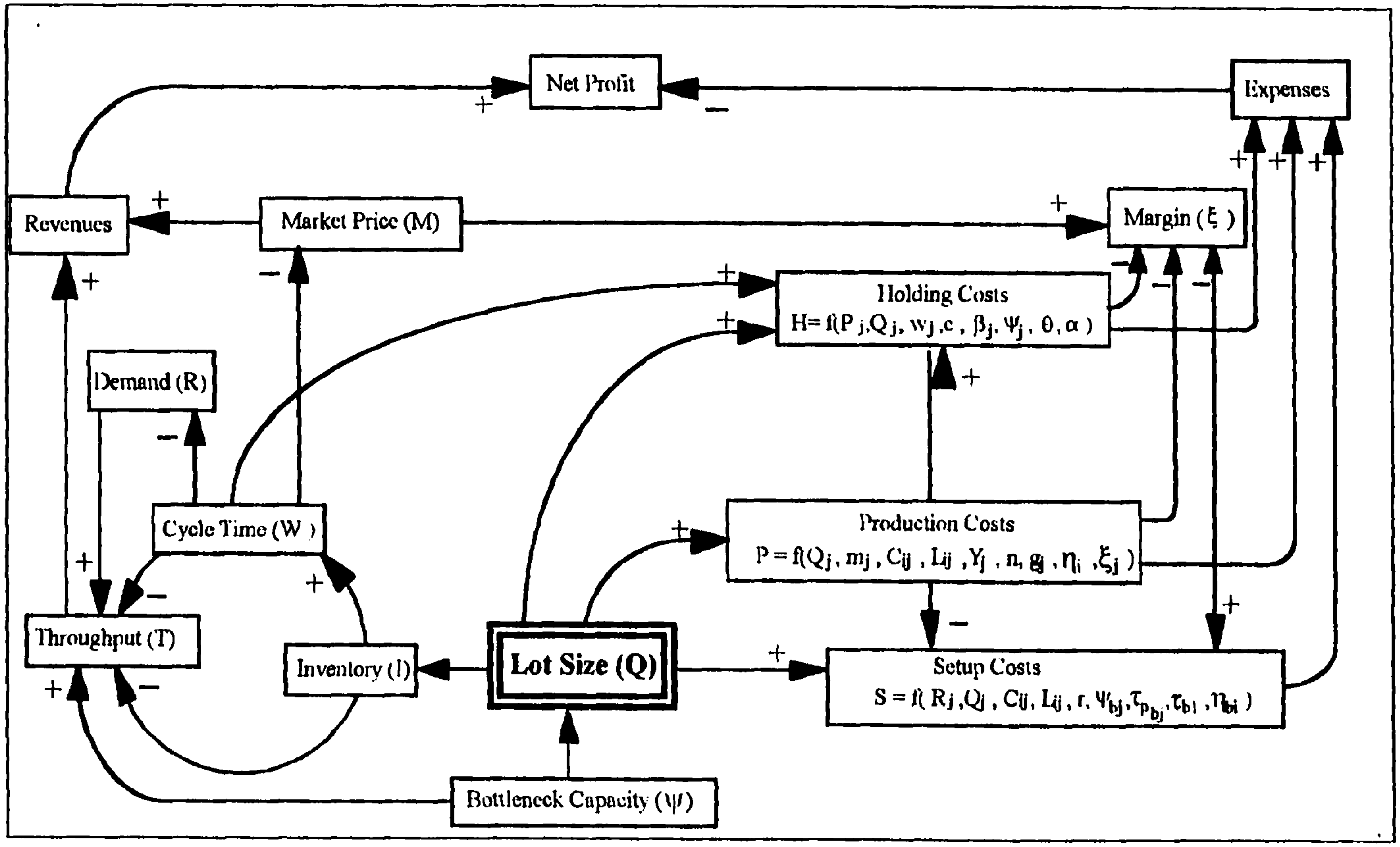

Figure 1-1: Relationship Diagram of the Production Cycle

needs.firm. Thus, optimally sized production lots can help meet these strategic.

EOQ based models are widely accepted baselines for making inventory scheduling decisions. Spence and Porteus (1987) have shown that, once the production system expands into a multiple operation system, the EOQ framework no longer applies. With the multiple operation production system, the demands placed upon upstream resources by the downstream resources are no longer stationary over time, but will depend upon lot size and scheduling. The literature suggests (reference Chapter 2) that long production runs are not efficient, and that sub-batching with operational overlap can improve manufacturing cycle times.

Another problem that exists in the usage of lot sizing models is that holding costs are considered to be a constant proportion of the production costs. Furthermore, they treat production costs as being constant across all lot sizes. There is also little understanding of the relationship of the number of in-process setups and the size of the sub-batched lots. Given these concerns, the problem to be addressed in this research is, **what effect does lot size have on the firm's net profits in a multiple product, multiple operation job shop environment?** Other questions that will be addressed in order to answer this research question are: (1) what effect does lot size have on production output in a multiple product, multiple operation job shop environment?, (2) what effect does lot size have on work-in-process in a multiple product, multiple operation job shop environment?, and (3) what effect does lot size have on product cycle times in a multiple product, multiple operation job shop environment?,

1.3. Objective Statement

Goldratt and Cox (1992) and Goldratt and Fox (1986) demonstrated the need for shifting the decision-making focus away from financial and cost accounting formulas and towards net profit, return on investment, and cash flow. In the theory of constraints (Goldratt, 1980; Goldratt and Cox, 1992; Goldratt and Fox, 1986; Stien, 1994; Umble and Srikanth, 1990), the success of an organization is measured by its ability to increase net profits while simultaneously increasing return on investment and cash flow.

Based upon these criteria, this paper develops a model that will assist an operations manager in determining the optimal lot size (sub-batch) for his or her production process. This model shall calculate the lot size that will maximize the firm's net profits. In order to accomplish this objective the relationships between gross revenues, production costs, overhead costs, and setup costs with respect to lot size must be determined, as depicted in Figure 1-1. These analytically derived relationships will be validated by both empirical data and a computer simulation model.

1.3.1. Deliverables

This research shall analytically and empirically derive and validate the following relationships: revenue generation versus lot size, production costs versus lot size, overhead costs versus lot size, and setup costs versus lot size. The next few paragraphs will discuss these relationships more fully.

Lately there has been a lot of discussion about the relationship between a product's cycle time and the firm's gross revenues. There are four generally excepted competitive strategies: cost, quality, flexibility, and time. The most recent of these strategies is time. It is believed that as a firm's lead time for a product is decreased one or both of the following benefits should result. First, the firm should be able to charge a premium price for that product. Second, there should be an increase in the number of orders for that product. Because of the relationship between cycle time and throughput (Little,

1961) and the relationship between cycle time and lot size (Enos,1993; Porteus, 1985; Potts and Baker, 1989), gross revenues are known to vary as a function of lot size;

$$R_j = f_r(Q_j, P_j). \qquad \text{Eqn. 1-1}$$

From this functional relationship an analytical model for calculating revenues shall be developed. Revenue generation is believed to be a function of market demand, market price, and the amount of finished product produced by the production system. The amount of product produced by the system is believed to be a function of bottleneck load capacity, lot size, and the number of lots being simultaneously processed at the bottleneck. The relationship of the above factors to revenue generation will be developed more fully in Section 5.4.

The costs relating to production are known to vary as a function of lot size;

$$P_j = f_p(Q_j, n_j). \qquad \text{Eqn. 1-2}$$

From this functional relationship an analytical model for calculating production costs shall be developed. As shown in Figure 1-1, production costs are believed to be a function of lot size, raw material costs, consumable materials costs, labor costs, process yield, the number of lots being processed simultaneously, and an opportunity cost. The opportunity cost associated with production costs is a function of bottleneck location and the firm's profit margin. The relationship of the above factors to production costs will be developed more fully in Section 5.5.

The costs relating to the firms overhead rate shall be presumed to be functionally dependent upon lot size;

$H_j=f_h(Q_j, P_j)$. Eqn. 1-3

From this functional relationship an analytical model for calculating holding costs shall be developed. Holding costs are believed to have two components: variable costs and fixed costs. Holding costs are also believed to be a function of several variables in the production system. The variables of interest in the determination of holding costs are production costs, lot size, the portion of the total production units started for a given product family, transaction costs, management's policy regime for production scheduling, the load capacity of the bottleneck for each product family. The relationship of the above factors to holding costs will be developed more fully in Section 5.6.

The costs relating to setup are known to vary as a function of lot size;

$C_s=f_s(Q, P_s)$. Eqn. 1-4

From this functional relationship, an analytical model for calculating setup costs shall be developed. Setup costs are primarily composed of opportunity costs, and secondarily composed of some variable costs. The variables of interest in the determination of setup costs are believed to be the product demand level, lot size, bottleneck load capacity, processing time, setup time, the number of lots being simultaneously processed at the bottleneck, labor costs, consumable materials costs, profit margins, and a learning curve. The relationship of the above factors to setup costs will be developed more fully in Section 5.7.

1.4. Definitions

Due to the inconsistent usage of the key terms in the literature, terms listed below shall conform to these definitions:

1. Batch is defined by the American Production and Inventory Control Society (APICS, 1995, p. 7) as "1) a quantity scheduled to be produced or in production. 2) For discrete products, the batch is planned to be the standard batch quantity, but during production, the standard batch quantity may be broken into smaller lots."
2. Batch processing as defined by APICS (1995, p. 7) is "a manufacturing technique in which parts are accumulated and processed together in a lot."

3. Lot is defined by APICS (1995, p. 45) as "a quantity produced together and sharing the same production costs and specifications."
4. Both a batch number and a lot number are defined by APICS (1995, p. 45)as "a unique identification assignment to a homogeneous quantity of material."
5. Lot number traceability is defined by APICS (1995, p. 45) as being able to track "parts by lot numbers to a group of items. This tracking can assist in tracing quality problems to their source. A lot number identifies a designated group of related items manufactured in a single run or received from a vendor in a single shipment."
6. Lot operation cycle time is defined by APICS (1995, p. 45) as the "length of time required from the start of a setup to the end of cleanup for a production lot at a given operation, including setup, production, and cleanup."
7. Lot size is defined by APICS (1995, p. 45) as "the amount of a particular item that is ordered from the plant or supplier or issued as standard quantity to the production process."
8. Lot traceability is defined by APICS (1995, p. 46) as "the ability to identify the lot or batch number

of product in terms of one or all of the following: its composition, purchased parts, manufacturing date, or shipped items."

9. Cycle time is defined by APICS (1995, p. 20) in two contexts, "1) in industrial engineering, the time between completion of two discrete units of production. 2) In materials management, it refers to the length of time from when material enters a production facility until it exits."
10. Yield is defined by APICS (1995, p.92) as "the ratio of usable output from a process to its input." Yield rate, as treated in this paper, is considered to be synonymous with processing quality.

1.5. Assumptions

The assumptions under which the proposed relations, and the subsequent model, are being developed under are as follows:

1. The production units are discrete.
2. The production line will require a major setup when the product family being fabricated is changed.
3. There are no major production line setups required for product model changes within the same family of

products, but there are minor setups at each operational step in the process. These minor setups involve the loading and unloading of production units, cleaning of the processing equipment as required, changes in consumable materials, and the loading of processing recipes (instructions).

4. Each product model within the same family utilize the same production resources.
5. Process flow sequencing for each product model may differ from model to model.
6. All units in a lot (sub-batch) are processed simultaneously (i.e., no splitting of lots during processing). This assumption further imposes the constraint that lot size may not exceed the load capacity of any operational step in the process.
7. Lots are moved between processing steps upon completion of current processing required (i.e., lot streaming).
8. Lots of differing product models are not mixed during processing at a given operational step.
9. Processing times, setup requirements, and processing capacity may be different at each operational step. Thus, idle time is allowed.

10. The processing capacity at each operational step is fixed.
11. There are no buffer limits on work-in-process inventories between operational steps.
12. Labor costs are divided into two categories: operating expense and overhead. Labor costs under operating expense are those labor charges directly related to production and setup times; otherwise, the labor charges are classified as overhead. An example of this is when a process step requires 30 minutes. Ten minutes of this time is for setup, another 10 minutes of the operators' time is directly involved with the process, and the final 10 minutes the operator is idle, or is used supporting another operation, while waiting for the process operation to complete. In this process step, 20 minutes of the operators' time is operating expense and 10 minutes is overhead. The labor rate (L) used in the modeling of the following propositions reflect the firms operating expense per unit of time.

1.6. Outline of Succeeding Chapters

This dissertation shall be organized as follows. Chapter 2 contains a literature review that discusses the current level of research in this area. Chapter 3 introduces some basic concepts about integrated circuit fabrication processes and the product flows that are typically found in a wafer fab. Chapter 4 discusses various research methodologies and presents the research method that shall be utilized in this thesis. Chapter 5 shall motivate the theorized relationships for the proposed analytical[1] model, and present the proposed model. Chapter 6 will discuss the development of the simulation model used in validating the theorized model, and present the findings from this simulation. Chapter 7 will discuss the data collected and analyze the data with respect to the theorized relationships developed in Chapter 5. Chapter 8 is the last chapter and shall summarize the results of this research and discuss the contributions, limitations, and future research goals for this work.

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[1] In this dissertation the terms "analytical model" and "theorized model" shall be synonymous.

CHAPTER 2

LITERATURE REVIEW

This chapter shall review the current literature on production control theories, lot sizing models that have been developed to facilitate the decision making process in these areas, and production scheduling and planning systems. Other areas in the literature that will be reviewed are process yield calculations, holding costs, and setup costs.

2.1. Production Control Theories

2.1.1. The Just-in-Time Production Control Theory

Just-in-Time (JIT) is defined by Chase and Aquilano (1995) as an integrated set of activities designed to achieve high volume production using minimal inventories of raw materials, work-in-process, and finished goods. This production system is based upon the concept that nothing shall be produced until it is needed. In theory, this system pulls product through the production system as follows:

1. As a unit of finished product is sold, the replacement unit is pulled from the last position in the system - final assembly.

2. Final assembly, needing a replacement for the unit just removed, pulls a replacement part from the next preceding work station in the system.
3. This process repeats itself all the way back to raw material release.

The two driving principles of the JIT production system are respect for people and eliminating waste. JIT addresses seven elements in its effort to eliminate waste. These elements are: focused factories, group technology, quality at the source, JIT production, uniform plant loading, kanban production control system, and minimized setup times.

JIT espouses that the ideal lot size is one unit(Chase and Aquilano, 1995; Tersine, 1994). In practice, the system works to minimize transit times between workstations and keeping transfer quantities small. The typical lot size is usually one-tenth of a day's production. These smaller lot sizes are possible only through reduced setup times (Funk, 1995). According to Funk (1995), these smaller lot sizes enable a factory to produce a broader variety of products, assemblies, and parts each day. Thus, increasing the factory's flexibility and decreasing its cycle time.

2.1.2. The Theory of Constraints

Goldratt (1980) asserted that production scheduling may be viewed as a three-stage process: setting the batch size, setting the priorities, and scheduling the finite capacities. In setting the batch size, the goal is to determine a batch size that will minimize the manufacturing costs per unit. The traditional view of this activity is to strike a balance between holding costs and setup costs. Larger batches relate to fewer setups and the associated labor costs, but also equates to longer product lead times and higher holding costs.

Goldratt points out the flaw with this approach as being that it is assuming that all of the saved setup times will translate into reduced costs. He contends that saving time on non-bottleneck resources only increases idle time. Saving time by reducing setups at a bottleneck will increase production throughput (Goldratt, 1980; Fox, 1983; Goldratt and Fox, 1986; Umble and Srikanth, 1990; Goldratt and Cox, 1992).

Today, the prioritizing of which jobs should be run first is based upon the estimated lead time of the product. This estimated lead time is in turn dependent on the estimated process time. The usual procedure for estimating the process time is to over look capacity constraints and calculate the time for each part as the sum of the processing times. Goldratt contends that priorities cannot be set without information regarding the finite capacity limitations of the process. Goldratt's conclusions about these two stages of the scheduling process are that we need to plan large batches to avoid losing time at the bottleneck, but must also be prepared to split those batches to avoid excessive buildups of work-in-process inventories at non-bottleneck resources. He also concludes that priorities can only be set after considering the finite capacity constraints of the system.

Goldratt (1980), Fox (1983), Goldratt and Fox (1986), and Goldratt and Cox (1992) have created a framework for scheduling production called "optimal production technology" (OPT). First, considerations must be made for more than just a single batch. Both process batches and transfer batches are needed. The transfer batch should be defined such that: (1) the process step or operation will not start unless there are sufficient parts to process a transfer batch, and (2) parts will be released for further processing in transfer batch quantities (i.e., lot streaming). Fox (1983) and Umble and Srikanth (1990) hold that the transfer batch size may not, and many times, should not be equal to the process batch. A process batch is an integral multiple of the transfer batch, and the transfer batch should be set separately for each job step. Traditional logic holds that, the process batch size should be fixed. With this new system, the process batch size should be variable (Fox, 1983).

OPT also needs a third batch called the "control batch." The control batch size is set at the convenience of the management. All associated documentation of processing activities and tracking of the batch is attached to the control batch.

Between each processing step, there is a buffer to hold parts that have just finished being processed by the previous processing step and are waiting in queue to be processed by the next step. This buffer allows for different size transfer batches at each processing step. Like the transfer batch size, the buffer size is set separately for each processing step.

Goldratt (1980) says that there are four general managerial parameters that describe the nature of the plant. The first parameter is the minimum machine time (MMT). This parameter controls the flow of materials through the production process. The mechanism that MMT uses in controlling the product flow is to set the minimum amount of time that a transfer batch must spend at each processing step. Thus, by setting a MMT policy regime at the i^{th} processing step of 100 minutes, if it takes 5 minutes to process a part, then the transfer batch size at that step is 20 units.

The second managerial parameter is the desired stock (DS) level. The DS policy regime defines the amount of safety stock (buffer) to be maintained at each processing step to guard against processing fluctuations in the system and insure a smooth product flow.

The third parameter is the flow parameter. This flow parameter is a correction for the MMT. It determines the smoothness of the product flow through the production system by trimming the size of transfer batches. By using this flow parameter the upper limit on the transfer batch size is determined by the product of the flow parameter times the transfer batch size of the preceding operation, where the flow parameter is some whole number like 4.

The final managerial parameter is the maximum batch limitation (MBL). This parameter provides a correction for the previous three parameters and is only applied to the front portion of the production line, where it is possible to produce excessively large quantities of product. The MBL trims either/or both the transfer batch sizes and the process batch sizes so that they are not larger than required to meet demand.

Creating a production schedule is a function of several items. Goldratt (1980) identifies some of the characteristics of a good schedule as follows: (1) a good schedule will show a level of full utilization for the bottleneck at all times, (2) a good schedule must maintain a low level of work-in-process, and (3) a good schedule must show realistic completion dates. The method outlined for this in Goldratt and Fox (1986), Goldratt and Cox (1992), and Umble and Srikanth (1990) is the drum-buffer-rope, where the product flow is set at just below market demand levels.

Comparing Goldratt's production planning and control system with the production lot sizing (PLS) model to be developed in this proposal, two similarities can be seen. The transfer lot size (Q) of the PLS model, with its lot traceability requirements imposed, would be analogous to the control lot in Goldratt's systems. The processing of multiple lots (ηQ) at a given machine in the PLS model would be analogous to the variable transfer lots in Goldratt's system.

2.2. Simulations

The objective of a simulation model in the job shop environment is to find the optimal solution to an n job, m machine problem based upon a given criteria. Frequently, the problem of interest is the scheduling of jobs with respect to different performance criteria. Another objective of simulation models is to learn something about the process or to make predictions about the behavior of the process.

Uzsoy et al. (1992) have reviewed the simulation work of several researchers. They found that the approach utilized by Dayhoff and Atherton (1984, 1986a, 1986b) in simulating the wafer fab environment to be representative of many other researchers' efforts. Their description of this approach is,

> this approach is based upon modeling a fab as a queuing network. The components of the model are wafer lots, products and process flows. Each product is associated with a sequence of process steps, called a product flow. Lots move from workstation to workstation according to the product flow. Batch processing is allowed, where a number of lots may be processed together, or a large lot broken up into smaller lots according to machine capacity. (Uzsoy et al., 1992, p. 52)

Spence and Walter (1987) investigated photolithography performance in the wafer fab based upon a throughput-cycle time tradeoff similar to that of Dayhoff and Atherton. The findings of this work showed that adding resources to the process would reduce cycle time, but there was also a diminishing return effect. They also found that as lot sizes were reduced, cycle time was improved greatly. Another finding of this work was that, as setups were reduced, that the effective capacity of the process was substantially increased.

Wu et al. (1994) investigated the differences between traditional production scheduling practices in the furniture industry and the optimized production technology introduced by Goldratt (1980). The models of the two systems made use of queue service disciplines that considered data other than just arrival time. The models initially utilized constant processing times to validate them. Then random variations were introduced using symmetrical triangular distributions. Wu et al. also utilized the approach of scanning a queue of waiting jobs for identical jobs to the one just processed, thus saving a setup. Where no identical jobs were found, the first-come-first-served sequencing rule was applied. Using the makespan criteria, this study found that the drum-buffer-rope system utilized in optimized production technology out performed the traditional method in every case.

Abdallah (1995) looked at knowledge-based simulation models where the simulation was used to help build the knowledge base. He defined the objective of a knowledge base for a scheduling system as being able to provide a decision which could be used in solving situations such as: increasing work-in-progress, machine idleness, job due dates not satisfied, machine breakdown, unavailability of labor, and rejection of certain operations or materials.

Another factor in scheduling performance is job characteristics. Job characteristics include: statistical characteristics of the processing time (i.e., mean and standard deviation), technological order matrix of the job, distribution of due dates, setup times, and manufacture to stock or at demand. To investigate the effects of these factors, Abdallah utilizes simulation experiments to build a knowledge base of the job shop environment.

Koh, de Souza, and Ho (1995) introduced a new concept called direct database simulation. The direct database simulation uses rational database data as the simulation model for simulation-based scheduling in the job shop environment. Using this technique, they where able to achieve improvements of up to 20% in job tardiness and machine utilization.

Glassey and Resende (1988) simulated a semiconductor production line utilizing a single bottlenecking resource to test several release and dispatching policies. They found that, in all cases, the first-in-first-out (FIFO) release policy for avoiding the starvation of the bottleneck yielded the best results.

Wein (1988) extended this exercise using varied bottlenecking conditions by also examining the relationship between yield and cycle time. One key assumption that is used in this work is that the mean number of defects per wafer is a linear function of the time that the wafer spends in the fab. The basis of this assumption is that, the longer a wafer spends in the fab, the greater the probability of contamination.

Wein showed in this work that the throughput rate is not a monotonically increasing function of the material start rate. He also found that FIFO sequencing rules that were based upon the bottlenecking machines loading resulted in the best performance. The major parameter in the model to be developed in this thesis is the bottlenecking operations load capacity.

Neural networks are increasingly being used to model complex systems with numerous variables. Rietman and Lory (1993), Mocella et al. (1991), and Himmel et al. (1992) worked with neural network models in studying the plasma etching process. Mocella's model investigated the effects of rf power, pressure, magnetic field, gas flow rate and wafer cooling on the process optimization of the plasma etching rate. Himmel's model also focused upon the process optimization of the plasma etching rate. In his model, the input variables where rf power, pressure, electrode gap, and gas flow rate. Rietman and Lory's (1993) work was focused upon the predicting of the final oxide thickness in the source and drain regions of CMOS devices.

Gurnani et al. (1992) modeled the reentrant flows of the typical semiconductor fabrication process. They call this flow pattern a serial-batch system because there are two stages. The first stage is comprised of machines which process units serially. The second stage is capable of processing units in batches. This work also describes loading polices for the batch machines with uncertain arrivals. In their model, they utilize concepts of renewal theory and control of batch queues for computing dispatch quantities. They also consider multiple identical machines. Production Planning and Control Systems

2.3. Planning Systems

2.3.1. Materials Requirements Planning (MRP)

MRP is a scheduling methodology that is based upon dependent demand. According to Chase and Aquilano (1995), material requirements planning (MRP) is an easily understood approach to the problem of determining the number of parts, components, and materials that are needed to produce the end items. This system also provides a time schedule specifying when each part, component, and/or material should be ordered or produced. It develops this schedule by reaching into the master production schedule, the bill of materials file (also known as the product structure records), and the inventory records file.

The main purposes of the MRP system is to control inventory levels, assign operating priorities, and plan capacities for loading the production system (Chase and Aquilano, 1995). The operating philosophy of MRP is to expedite materials when their lack would delay the overall production schedule, and to de-expedite or delay those materials when the schedule falls behind.

MRP primarily focuses upon batch requirements. Its fixed lot sizing rules establish quantities for planned work orders (Millard, 1996). In general, MRP does not calculate transfer lot sizes. MRP determines the process batch sizes needed to meet requirements for one or more periods. The four most common lot-sizing techniques utilized by MRP systems are: (1) lot-for-lot, (2) economic order quantity, (3) least total cost, and (4) least unit cost (Chase and

Aquilano, 1995). Reference section 2.4 for discussion about these models.

The most utilized of these four techniques is the lot-for-lot method. In this method the planned order size is set exactly to match the net requirements. For in-house usage this method produces exactly what is required for the period with no production units carried over into future demand periods. The primary limitation of the lot-for-lot method is that it does not take into account setup costs or capacity limitations (Chase and Aquilano, 1995). Brooking et al. (1995) also points out that a lot-for-lot ordering policy implies that ordering costs (setups) are not significant.

2.3.2. Enterprise Resource Planning (ERP)

Keller (1995) describes enterprise resource planning as follows: (1) an integrated set of financial, distributional and manufacturing software, (2) an expanded and altered functional model of MRP II, (3) proactive, (4) rules based, (5) adaptive. Hicks and Stecke (1995) emphasized that ERP was concerned with making sure that a firm's manufacturing decisions are not made without taking into account their impact on the supply chain. They said that, production decisions are affected by and affect all of the other major areas in the business, and as such needed to take into account all of the interactions within the business.

ERP, as discussed in the literature, does not specifically plan or balance the production line resources, or determine lot sizes. It utilizes the information and planning of either, or both, MRP II and FRP for these decisions. What it does do is look at how these plans and decision affect suppliers, distributors, and the other functional areas within the business.

2.3.3. Finite Resource Planning (FRP)

Millard (1995) describes finite resource planning (FRP) as, a process for maximizing a company's throughput by identifying resource constraints and managing them effectively. This planning system is able to accomplish this by accounting for the load of each resource based upon setup time, process run time, and the expected idle time. FRP identifies system constraints through the utilization of load to capacity ratios. High-ratio resources (bottlenecks and capacity constrained resources) have the greatest control on the systems throughput.

FRP systems provide constrained resource based lot sizing (Millard, 1995). Through the dynamic utilization of bill of material explosion and implosion, and simulation tools, these systems are capable of determining what the best due date performance will be by answering the following questions: (1) to what extent is overtime needed, (2) how should jobs be combined to optimize setups, (3) how should lot sizes be changed, and so on.

Millard (1985) points out some of the differences between MRP/MRP II and FRP systems as:

1. MRP II can never achieve high on-time delivery ($\geq$60%), because it was never intended to provide the final, detailed scheduling decisions.
2. MRP II does not collect and store information about status, nor does it address setups and sequencing for effective response and asset utilization.
3. MRP II rarely knows the difference between machines within a work center.
4. MRP II does not have much information regarding processing specifics, such as setups, machine speeds and capabilities, part routings, etc.
5. MRP II is not generally concerned with the maintenance schedule and availability of individual machines. Because of this Hess (1995) refers to schedules from MRP II as "infinite" schedules.

6. MRP II builds plans based upon estimates, averages, and queuing allowances, instead of determining the actual, realistic start and end time of jobs.

Other criticisms of MRP/MRP II are that it has traditionally served as a tool for addressing medium to long range planning and as such is marginal for real time decision making (Hoy, 1996). MRP II also does not provide an effective means for determining real-time availability information, or even an answer to, "can I build it?"

From the literature, the greatest difference between FRP and MRP based systems in the area of lot sizing is that MRP is a batch sizing system and FRP, like TOC, uses variable transfer lot sizes to load the different resources in the production line. To some degree, the literature implies that MRP II acts like FRP and TOC with respect to transfer lots except that it bases its planning upon estimates and fixed lead times (Gilman, 1995) instead of real time information and calculations. Also, none of these systems appear to consider net profits as a performance criteria.

FRP differs from ERP in that, ERP utilizes the plans and decisions from FRP to investigate their impact upon the firm and it's supply chain. ERP, in and of itself, does not perform load and utilization analysis on the finite resources of the production line.

2.4. Lot Sizes

2.4.1. Continuous Demand Based Lot Sizing Models

The classic EOQ model was first presented by F. W. Harris (1990) in 1913. Originally intended as a practical tool for industry, this model uses the trade-off between inventory holding costs and the tangible costs of ordering or setup as illustrated in Figure 2-1 to determine an optimal order quantity (Erlenkotter, 1990; Tersine, 1994). This cost function was determined to be:

$$Min\{TVC\} = Min\left\{\frac{QI_h}{2} + \frac{DS}{Q}\right\} \qquad \text{Eqn. 2-1}$$

where, TVC = Total variable costs, D = market or contract demand in units per time period, Q = order quantity in units per lot, S = setup costs in dollars, and I_h = inventory holding or carrying costs in dollars per time period. In all the models reviewed, holding costs were considered equivalent to a portion of the production costs as calculated by:

$$I_h = FP \qquad \text{Eqn. 2-2}$$

where, F is an overhead factor, and P is the production cost per unit of finished product in dollars. By setting the first derivative with respect to quantity equal to zero and solving for Q, the following economic order quantity model was derived to be (Burns and Austin, 1985; Erlenkotter, 1990; Harris, 1990; O'Grady and Byrne, 1988; Tersine, 1994):

$$Q^* = \sqrt{\frac{2DS}{I_h}} \qquad \text{Eqn. 2-3}$$

where, Q* = the optimal lot size.

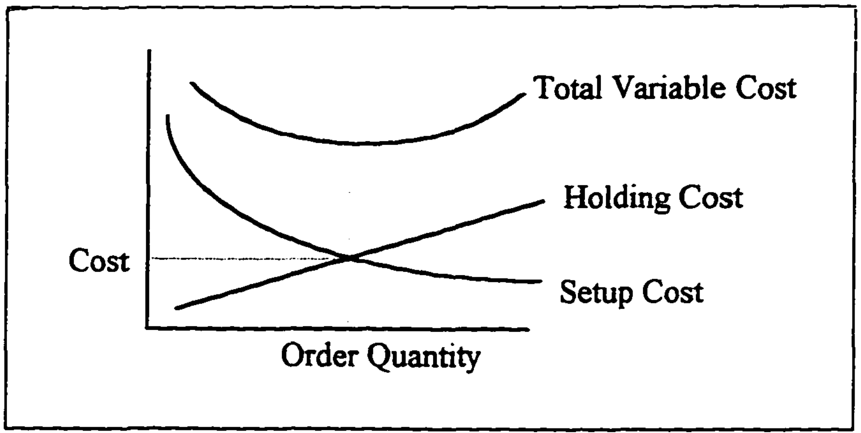

Figure 2-1: The Relationship between Holding Costs and Setup Costs
Source: Tersine (1994)

Firms that produce the product being ordered in close proximity to the point of need have a similar but slightly different problem. For such firms, it is possible to begin providing the product at the point of need well before the entire order is completely manufactured. Faced with having to produce the finished items while simultaneously supplying demand, these firms need to calculate the production quantity that will minimize total costs.

In 1918, E. W. Taft (Erlenkotter, 1990) developed a version of the EOQ model that dealt specifically with this finite production problem, called the EPQ model. In this model, the following expression is utilized to determine the optimal lot size(Burns and Austin, 1985; Erlenkotter, 1990; Tersine, 1994),

$$Q^* = \sqrt{\frac{2DS}{I_h(1-\rho)}} \qquad \text{Eqn. 2-4}$$

where, $\rho = D/\pi$ which is the process utilization, π is the maximum possible throughput of the production system, also known as capacity, and $(1-\rho)$ is the process idle time. For instantaneous replenishment (i.e., $\rho = 0$) it is easy to show that this formula reduces to Eqn 2-3. The problem with this model is that, because of queuing effects, the inventory carrying costs will explode as utilization (ρ) approaches one (1).

Abboud and Salameh (1987) proposed a model for determining the optimal order quantity that would minimize the total inventory cost per unit time for the finite production model under the effect of machine unavailability for a certain period of time where back ordering of items is not allowed. In this model, the minimum total inventory cost per unit time can be obtained by first calculating the optimum inventory level for the case in point, then calculating the optimal order quantity.

Szendrovits (1975) presented a model that assumes a constant lot size is manufactured through several operations with only one setup at each stage, but transportation of sub-batches allows an overlap between operations to reduce the manufacturing cycle time. The objective of this research is to determine the functional relationship between the sub-batch size, the manufacturing cycle time, and the average work-in-process level. In some industries, work-in-process inventories represents as much as sixty percent of the capital investment that the firm has in its total inventory. From this work, Szendrovits (1975) shows that, contrary to the widely accepted doctrine, long production runs were not efficient. In fact, it is shown that the EPQ model always derived a batch size considerably larger than optimum.

Hum and Sarin's (1991) work expands the EPQ model to incorporate the concepts of net profit maximization and capacity constraints. This model is used in determining the profit maximizing mix, or quantities, of multiple items. Their model for computing these optimal lot sizes at a bottleneck facility is:

$$\text{Max } \Sigma\left\{\xi_i Q_i - \left(S_i \frac{D_i}{Q_i} + \frac{I_{h_i} Q_i}{2\left(D_i / Q_i\right)}\left(1 - Q_i \tau_i\right)\right)\right\}, \quad \text{s.t. } D'_i \le Q_i \le \overline{D}_i \qquad \text{Eqn. 2-5}$$

where, Q_i = the number of units of the i^{th} product to be produced and consumed per unit of time, τ_i = the time required to produce one unit of the i^{th} product, I_{hi} = the holding cost per unit of time for each unit of the i^{th} product, S_i = the cost per setup of each facility to produce the i^{th} product, ξ_i = the net contribution to profit per unit of the i^{th} product produced and consumed (net revenue less variable unit production costs), D'_i = the lower bound on demand for the i^{th} product ($D'_i > 0$, i= 1, 2,...), $\overline{D}_i$ = the upper bound on demand for the i^{th} product. Even though this model supports the goal of the firm better than previous EOQ-based models, it still does not provide support for operational level planning. This model also has many of the same limitations as other EOQ-based models, such as, it does not consider process quality, cycle time, resource capacities, etc.

2.4.2. Discrete Demand Based Lot Sizing Models

Chase and Aquilano (1995) describe the least total cost (LTC) method as a dynamic lot-sizing technique that calculates the order quantify by comparing the carrying cost and the setup costs for various lot sizes and then selects the lot in which these two costs are approximately equal. This method is also known as the "Silver-Meal" algorithm (Tersine, 1994). This algorithm calculates the lot size as follows:

$$\frac{\mathrm{TRC(y)}}{\tau} = \frac{O_c + PF\sum_{w=1}^{\tau}(w-1)D_y}{\tau}, \qquad \text{Eqn. 2-6}$$

where, O_c is the ordering cost per order, F is the holding cost fraction (overhead rate) per period, P is the production or purchasing cost, TRC(y) is the total relevant cost over y periods, τ is the time supply of the replenishment in periods, and D_y is the demand rate in period k. The Silver-Meal algorithm guarantees only a local minimum for the current replenishment. Tersine notes two cases where it does not perform well as being: (1) when the demand rate decreases rapidly with time over several periods, and (2) when there are a large number of periods with zero demand.

The least unit cost method is the same as the least total cost, except that instead of dividing through by the number of periods, the costs are divided through by the number of units ordered in the replenishment period. This calculation is expressed as:

$$\frac{\mathrm{TRC(y)}}{\sum_{w=1}^{r}\mathrm{R_k}} = \frac{O_c + PF\sum_{w=1}^{r}(w-1)D_y}{\sum_{w=1}^{r}\mathrm{D_y}}. \qquad \text{Eqn. 2-7}$$

Thus, the replenishment quantity is:

$$Q = \sum_{k=1}^{T}\mathrm{R_k}\,. \qquad \text{Eqn. 2-8}$$

2.4.3. Fixed Lot Sizes

Traditional batch processing restricts the movement of units within the batch between operation steps in the process to an all or none situation. Thus, in addition to normal queue time, an idle time is imposed while completed units are waiting for the incomplete units in the batch to finish processing. The larger the batch size the longer these idle periods willed be.

2.4.4. Lot Streaming

Lot streaming, with overlapping operations, accelerates the progress of work through the production facility. Another advantage of lot streaming is that, if partial shipments of an order can be made, the first units in a batch can be delivered to the customer early.

Trietsch and Baker (1993) have defined lot streaming as the process of splitting a production batch into sub-batches (lots), and then scheduling these lots in an overlapping fashion, in order to accelerate the batch's cycle time through the process. Though lot splitting was first addressed by the literature in the mid 1970's, it is not a new concept. The practice has been going on informally in job shops for a long time.

Goldratt (1980) and Fox (1983) noted that cycle time could be reduced by utilizing smaller transfer lots than process batches. Kulonda (1984) said that, cycle time could be further reduced by choosing the optimal lot size or by using more than two lots per batch. In these situations, and in Goldratt and Fox (1986), Goldratt and Cox (1992), Stien (1994), and Umble and Srikanth (1990), the concept of lot streaming was advocated but a methodology for the determination of an optimal lot size was left unexplained. Baker and Pike (1990) said that, there is a limitation on the number of lots that a given shop can handle that is imposed by the capability of the information system to track lots in the shop. They also said that, this limitation may reflect a constraint that results from the number of carriers in the shop, the design of the processing equipment, the packaging requirements of vendors or distributors, or the tracking of individual lots for subsequent activities such as field service or warranty work.

A formal methodology for determining the optimal lot size was presented by Trietsch (1987), Baker (1987), and Trietsch and Baker (1993). Trietsch (1987) addressed the problem as one of optimizing lot sizes under a budget on the cost of transfers. Assuming that a budget for the total transfer cost is given, this approach balances the combination of budget and transfer costs such that the resulting transfers are feasible for the available transportation equipment. Baker's (1987) solution imposed the requirement of lot integrity, thus the number of lots is given and constant. Baker's algorithm uses the equally sized lot case with intermittent idling allowed.

Trietsch and Baker (1993) investigated lot streaming models that can be incorporated as modules in Material Requirement Planning (MRP) systems. The one-machine, two-machine and three-machine cases were investigated. These models also included both continuous and discrete lot size models. Trietsch (1987) found that in general the cycle time of an order is minimized if there is just one item in each sublot. Trietsch and Baker (1993) point out that this solution may be impractical due to increasing transaction costs and the limited handling resources actually available in most manufacturing firms.

In the basic model for multiple operations investigated by Trietsch and Baker (1993), the transfer costs (c_i) of lots from the i^{th} machine to the $i^{th}+1$ machine are accounted for. They also impose a budget on the total cost of transfers. They found that, the minimum cycle time occurs with variable lot sizes (lot size can change from machine to machine) and when idling is allowed.

Baker and Pyke (1990) presented an algorithm for solving the two-sublot problem more efficiently than linear programming and discussed some implications for bottlenecks. Though they found that no efficient optimization procedure yet existed for the m machine case, they recommended the approach taken by Campbell, Dudek, and Smith (1970). This approach was to create a derived problem by aggregating data in the m-machine problem to form an analogous two-machine problem, then solve the two-machine problem. Some of their findings suggested that the utilization of equally-sized sublots was a viable procedure given its simplicity and practicality.

Campbell, Dudek, and Smith (1970) also found that, as the number of sublots increased, the benefits of lot streaming showed diminishing marginal returns. This finding agreed with Potts and Baker's (1989) findings where the two-sublot solution achieved up to fifty percent of the potential benefit attainable from multiple sublots. The model used by Baker and Pyke required two bottlenecks (one of which was really a capacity constraint resource). This model reinforced the concept that lot sizing may influence the location of bottlenecks.

Potts and Van Wassenhove (1992) looked at the integration of scheduling with batching and lot-sizing. The primary variables in the models investigated were processing time and setup times or cost. They compared the model over several environments, such as, the single-machine problem, the parallel-machine problem, and the flow-shop and open-shop problems. In each of these cases, the critical decision parameter was completion time of the job. With respect to lot-sizing and lot streaming, they concluded that at best the problem is only satisfactorily solved for a single job case, and that even less is known about lot streaming in the flow shop environment.

2.4.5. Criteria Appropriate for Determining the Optimal Lot Size.

The primary methods of optimizing lot sizes that were suggested by the literature were: (1) discrete batch calculations such as the methods utilized by MRP, (2) continuous batch calculations such as the EOQ, (3) simulations with either fixed lot sizes or variable lot sizes. The first two methods, discrete and continuous batch calculations, both have numerous versions. In each of the versions, a different set of assumptions or measurement criteria are utilized. In all of these methods, the predominant measure of an optimal lot size was either make-span or total cost.

Tersine (1994) concluded the following concerning the appropriateness of the different lot sizing methods;

> Some of the assumptions made in regard to classical inventory models (EOQ, EPQ, and EOI) are inappropriate for demand which varies from period to period. Since demand does not always occur at a constant rate, but can follow a discrete pattern, the indiscriminate use of fixed order sizes can result in larger than necessary inventory costs for these situations. Therefore, several alternative, optimum-seeking approaches for determining lot sizes when the demand rate is not constant have been developed.
>
> These lot sizing approaches focus on controlling the costs of holding inventory and processing orders. None of the approaches, with the exception of the Wagner-Whitin algorithm, assures an optimal or minimum cost solution for time-varying demand patterns. The more complicated Wagner-Whitin dynamic programming algorithm can minimize cost for a deterministic, fixed horizon demand series. For this reason, it often serves as a benchmark against which to measure the performance of nonoptimal but less complex lot sizing approaches....
>
> The heuristic approaches are similar in the way they arrive at lot sizing decisions... Lot-for-Lot ordering seeks to minimize holding costs by never batching any orders... The silver-Meal algorithm selects a lot size that includes an integer number of period requirements such that the total relevant costs per time period for the duration of the lot size are minimized... The least unit cost heuristic selects a lot size for

> an integer number of period requirements such that the total variable cost per unit for the duration of the lot size are minimized....
>
> All of the lot sizing approaches seek to minimize costs for a single item and do not consider items as part of a multistage inventory system. They do not address the cost consequences of lot size for the system as a whole, nor do they consider any workload balances in a multistage system. When other factors are given consideration, some lot sizing policies have more advantages than others. Even through the Wagner-Whitin algorithm can assure optimality in some circumstances, it may not perform as well as simpler techniques in a rolling schedule environment. (p. 196)

With respect to the final comments made by Tersine, simulation models may actually be the only feasible method for determining the optimal lot size in a rolling schedule environment.

2.5. Process Yield

Lot sizing decisions can be affected by the presence of defective units in the order. Silver (1976) lists several factors which could cause discrepancies between the quantity ordered and the usable quantity received. These factors are clerical errors, damage in transit, inadequacies of raw materials, and rounding-off by suppliers to achieve economies of scale. In a production process, the following items can also account for shortages in the usable final product: variances in the processing, operator error, equipment failures, handling errors, variances in incoming materials, and defective raw materials.

There are three schools of thought on the occurrence of defects. The first school of thought is that the occurrence of defects is independent from one production unit to the next. The second school of thought is that the creation of defects is dependent. The third school of thought is a combination of the other two schools.

Levitan (1960) contended that in the case of discrete units, it can be assumed that each unit has the same probability of being defective, independent of the other units being processed. Porteus (1986) assumed that once a defective unit is produced, all subsequent units in the lot will be defective. Shin (1980), Lee and Yano (1985), Ehrhardt and Taube (1986) and Gerchak et al. (1988) proposed that the yield variability is a product of the input level and a random multiplier which is independent of the input level.

Porteus (1986) said that, once a production process started to drift out of specifications, it would continue to do so. The optimal order quantity proposed is derived from the conventional EOQ model for total cost plus the cost of rework. The cost of rework is calculated as the rework cost per unit times the expect number of defects per batch. The expected number of defective units in a batch of size Q is calculated as,

$$Q-[q'(1-q'Q)/q] \qquad \text{Eqn. 2-9}$$

where q is the probability of the process going "out of control," and q' = (1-q). This work also discusses the option of investing in the reduction of setup costs. The conclusion was that investments in quality improvement will substantially reduce total costs. It was further concluded that, even without the consideration of quality, investments in the reduction of setup costs would again substantially reduce total costs.

Even though production line setups are significantly more costly than the operational setups of a single machine and the costs of quality improvement for a process are greater than improvements at a finite point in the process, the same relationships found by Porteus (1986) should hold.

2.5.1. Calculating Process Yield Rates

Porteus (1986) showed that by considering quality of the process, the optimal batch size calculated by EOQ-based models will be reduced. The model developed by Porteus (1986) showed a significant relationship between process quality and batch size. From the quality control literature, process quality is related to the process means location with respect to the product's specified target value, the variance in the process means location, and the overall product specification's tolerance range. These relationships can be measured and the process overall quality capability calculated with capacity indices. Figure 2-2 illustrates the process relationships that will be discussed in this section.

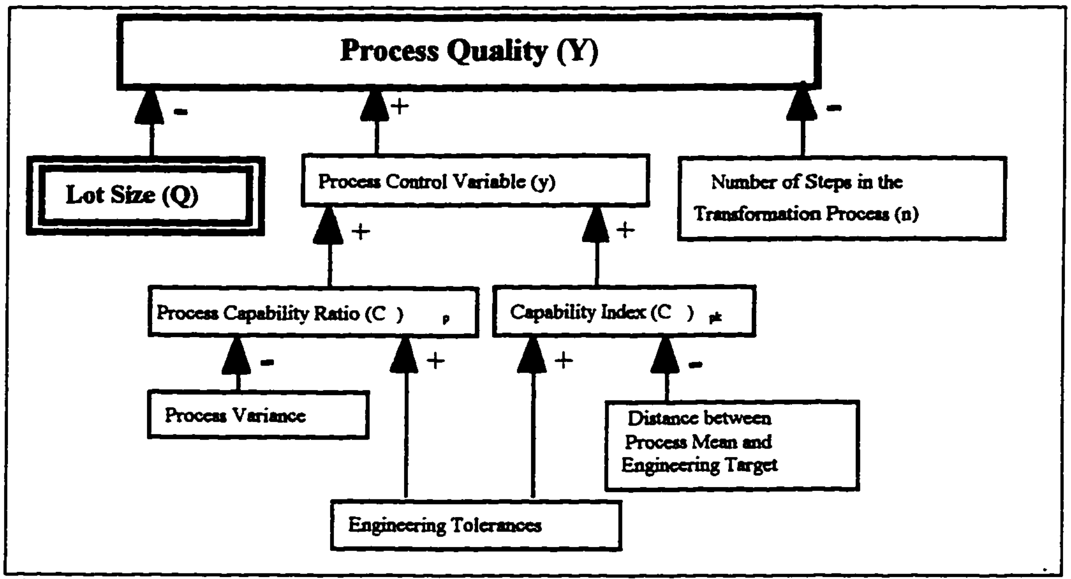

Figure 2-2: Relationship Diagram for Process Yield Rate

<u>2.5.1.1. Process Capability Indices</u>. By assuming that the engineering tolerances adequately reflect customer requirements, the quality of the process can then be represented by the process yield rate. Process capability indices were developed to measure and describe the relationship between the process' mean and variance, and the product's specifications. These indices are used

extensively in industry to provide information on process performance.

Kushler and Hurley (1992) and Kolarik (1995) assert that the quality of a manufactured product is ultimately determined by the level of customer satisfaction. They also say that a quality variable is any observable characteristic of the product or service, or of the processes that produce it, which can affect the customer's satisfaction. The process mean and the process variation are two such quality variables. The capability of a process depends on the relationship of the process mean's distribution to the product specifications. In order to determine and track the variation of a process with respect to the product specifications, indices such as C_p and C_{pk} where developed. The earliest process capability index was the C_p (Pearn et al., 1992). The form of this index is

$$C_p = \frac{USL - LSL}{6\sigma} \qquad \text{Eqn. 2-10}$$

where USL is the upper specification limit, LSL is the lower specification limit, and σ is the standard deviation of the variables.

> The index C_p depends only on the spread of the distribution. If the process is in control, then σ can be viewed as representing the current level of common cause variation. Hence the index C_p can be considered a measure of the process potential,

> the best performance attainable without fundamental changes to the system. (Kushler and Hurley, 1992, p. 190)

The index C_p gives a measure of the dispersion of the process with respect to the product specification limits. As such, it is insufficient in totally describing the process. The location of the process mean must also be described so as to avoid the case where the $C_p = 1.0$ and $\mu \neq M$, where μ is the process mean and M is the specification target value. Therefore, the C_{pk} index was proposed. Using the estimated standard deviation of the process

$$\hat{\sigma} = \sqrt{\frac{1}{(n_s - 1)} \sum_{i=1}^{n_s} (X_i - \overline{X})^2} \qquad \text{Eqn. 2-11}$$

the form of the C_{pk} index is

$$\hat{C}_{pk} = \text{min}\textit{imum}\left\{\frac{USL - \mu}{3\hat{\sigma}}, \frac{\mu - LSL}{3\hat{\sigma}}\right\}. \qquad \text{Eqn. 2-12}$$

2.5.1.2. Inferences on the Process Capability Index.

From the C_p and C_{pk} statistics the probability of nonconformance for the process can be computed as follows (Pearn et al., 1992)

$$2\Phi(-3C_p) \qquad \text{Eqn. 2-13}$$

and will never be greater than

$$2\Phi(-3C_{pk}) \qquad \text{Eqn. 2-14}$$

where, $\Phi(\ )$ is the area under the cumulative standard normal distribution curve for the z-score equal to $(-3C_{pk})$ (Pearn et al., 1992). Thus, the yield at each process step can be expressed as,

$$Y_i = 1-(2\Phi(-3C_{pk})). \qquad \text{Eqn. 2-15}$$

Given n steps in the process, the process yield (Y) can be approximated by,

$$Y = \bar{Y}_i^n. \qquad \text{Eqn. 2-16}$$

2.6. Setup Costs

As mentioned in the previous section, Porteus (1986) found that investments in the reduction of setup costs would again substantially reduce total costs, thus reducing the optimal batch size. Spence and Porteus introduce a model that helps to interpret the improved quality control that results in reduced setups. The importance of reduced setups is that (1) either more time is available for production processing or conducting more frequent setups, or (2) facility operating hours can be reduced.

Karmarkar (1983) said that there are no real setup costs in the sense of cash flow. This case arises when there are no materials consumed in the setup and when labor costs are considered to be fixed cost and thus accounted for as overhead. This view point on labor costs is also supported by Goldratt and Cox (1992). It is Goldratt and Cox's contention that the only true cost of setups is through the impact of the setup on throughput.

2.7. Holding Costs

Being able to determine an appropriate fixed overhead rate is important for the assigning of costs to production activities, budgeting, and product pricing. Grinnell and Mills (1985) proposed that the determination and assignment of fixed overhead rates should not be based upon a single measure, but upon a combination of measures dependent on the situation. There are three specific measures that management typically uses for determining overhead rates: expected activity, normal activity, and practical capacity.

Expected activity and normal activity are both a reflective measure of the anticipated capacity utilization. Grinnell and Mills (1985) define expected activity as being the anticipated level of capacity utilization for the coming period. They also define normal activity as being representative of the expected average utilization of capacity over multiple periods.

The basic difference between the three concepts hinges on different interpretations of the term "capacity" and the use of different time periods for measuring that capacity (Grinnell and Mills, 1985). Fixed overhead costs are those costs that are not expected to significantly change over time with respect to changes in production activity. Grinnel and Mills make a further distinction in these costs as either "committed" or "managed" costs. They define committed overhead costs as those that are related to the possession of property, plants, equipment, and the existence of a basic organization. Examples of committed overhead costs are depreciation on plants and equipment, rental payments associated with non-capitalized long-term lease obligations, property taxes, property insurance, and the salaries of key personnel. Managed overhead costs are defined as those costs which are subject to periodic adjustments. Examples of this type of cost include costs of non-key supervisory and other salaried personnel, short-term lease obligations, employee training, management consulting fees, and various support activities. Grinnell and Mills (1985) advocate that fixed overhead costs should be assigned to production using a predetermined application rate comprised of two parts: the fixed overhead rate based on expected activity and the fixed overhead rate based on normal activity.

According to Spence and Porteus (1987), there are typically two costs associated with holding inventory: financial and physical holding costs. Financial holding costs are defined as those costs that capture the opportunity cost of capital tied up in inventory that is produced before it is needed. Physical holding costs are defined as those costs that are incurred because of the existence of physical inventory on hand. Porteus (1985) found that financial holding costs depend only on the batch sizes being utilized and not on the physical inventory levels.

In conventional cost accounting systems, there exists a two-stage procedure for the allocation of costs (Brinker, 1992). the first stage involves the assigning of indirect costs to various cost pools. The second stage allocates these pooled expenses to products. In order to make these allocations some measure such as an allocation base or an activity driver are used. Thus, overhead expenses are assigned to products by multiplying the burden rate of each cost pool by the allocation base. In this type of system, if a regression analysis was made of a firm's operation expenses the fixed, or intercept, parameter would represent the overhead costs, and the variable parameter(s) would represent the direct costs of production. There would also be some expense that would fall completely into the overhead cost pools, such as taxes and depreciation, and others, such as materials, would fall totally into the direct costs pool.

With modern activity based costing systems the assignment procedure tries to take advantage of the hierarchical view of activities. In this procedure, batch-level costs are divided by the number of units in the batch, product and facility costs are divided by the number of product units produced, then these are summed and added to the unit-level costs (Brinker, 1992). According to Robin Cooper (1992), activity based costing (ABC) suggests that an inappropriate degree of variability in all manufacturing cost vary with the number of units produced. Cooper (1992) asserts that batch-related costs can only be reduced by decreasing the number of batches, or by performing batch-level activities more efficiently, not by reducing the number of units produced.

2.8. Lot Sizing Taken in Relationship to Cycle Time and Gross Revenues

There is very little, if any, literature explicitly done on this subject. But, there are some interesting relationships between lot size and cycle time, cycle time and costs, and costs and sales that imply a relationship between lot size and revenues.

From Little's Law (1961), W = IT, we know that the firm's cycle time (W) is equal to the product of inventory level (I) times the systems output (T). From Corbey and Jansen(1993), Enos (1993) and others, we know that lot size is directly related to inventory levels and throughput.

Fraser (1995) points out several advantages to shorter cycle times:

- Reduced work-in-process inventory;
- Fewer changes in customer orders once they have been released to production;
- Reduced inventory obsolescence in raw, work-in-process, sub-product, and finished goods;
- higher effective capacity, since throughput is faster when there is less of an inventory queue at each work center; and
- shorter order-to-cash cycle to get paid for production.

Work performed by Vickery, Droge, Yeomans and Markland (1995) from that reduced product cycle time can significantly impact the firm's performance in the following areas: return on investment, return on assets, return on sales, and market share. In Buxbaum's (1995) study of the Case corporation's turnaround, cycle time was directly linked to profitability.

Most authors agree that time as a competitive strategy is a formidable weapon. Shorter cycle times will result in better quality and greater flexibility. Both quality and flexibility will attract new customers, and in many cases allow the company to charge a premium price.

2.9. Summary

Throughout the relevant literature, there are a few common themes. The themes most often observed are: smaller lot sizes are better, shorter cycle times are better, and less inventory is desirable. Yet, Potts and Van Wassenhove (1992) concluded that there is not a good model for determining these items for the m-machine job shop environment. It was also found that there exists enough evidence to conclude that the drum-buffer-rope control system developed by Goldratt provides the best results in controlling a production system.

In all of the above cited models, the criteria for optimality was based upon the minimum cycle time schedule. The research presented in this dissertation sets the criteria for optimality based upon net profits. Other considerations looked at are: (1) the variability of holding costs with respect to lot size, (2) the variability of the number of setups with respect to lot size, and (3) process quality is considered.

From this review of the relevant literature, it can be seen that a model is needed that not only determines an optimal lot size for the multiple product, multiple operation job shop, but will determine this lot size based upon maximizing the firm's net profits using a bottleneck focus. The literature has also shown that this model should consider such elements of the job shop as; process quality, resource capacity, cycle time, and lot integrity.

Using the assumptions stated in section 1.5, the model being developed by this research is targeted at helping managers in the job shop environment make better decisions with respect to the processing of work through the shop. The specific environment that this work is focused on is batch processing. Texas Instruments, Inc., has agreed to support this research by providing both data from their production process and processing details on how their production operation works. Chapter 3 describes the basic process of integrated circuit fabrication.

CHAPTER 3

THE INTEGRATED CIRCUIT FABRICATION PROCESS

This research is focused on the job shop environment typically found in the semiconductor industry. The previous chapters described the problem that this research is investigating and present information from literature that is relevant to the problem. This chapter is intended to provide a basic understanding of the fabrication processes utilized in the production of integrated circuits.

3.1. General Description of Integrated Circuit Fabrication

Integrated circuits (IC) have become an important part of our daily lives. They are utilized in televisions, radios, computers, aircraft, communications equipment, and in many other applications, including automobiles, appliances, and credit cards. Modern wafer fabrication is one of the most exacting of production processes ever developed. Since the 1950's, tremendous amounts of resources have been expended in the development of the semiconductor industry world wide.

Uzsoy et al. (1992) divided the process by which integrated circuits are manufactured into four basic steps: (1) wafer fabrication, (2) wafer probe, (3) assembly or packaging, and (4) final testing. Steps 1 and 2 are typically referred to as "front-end" operations, while steps 3 and 4 are referred to as "back-end" operations. Many of the operations in the front-end are highly sensitive to contamination, and are performed in a clean-room environment. The research presented in this thesis is focused upon the shop-floor control of the front-end operation. Figure 3-1 illustrates a simplified product flow through a typical front-end operation or wafer fab. The solid lines in this illustration represent the generic flow, while the dotted lines represent the reentrant flows that are necessary to accomplish the multiple layering of the integrated circuit design.

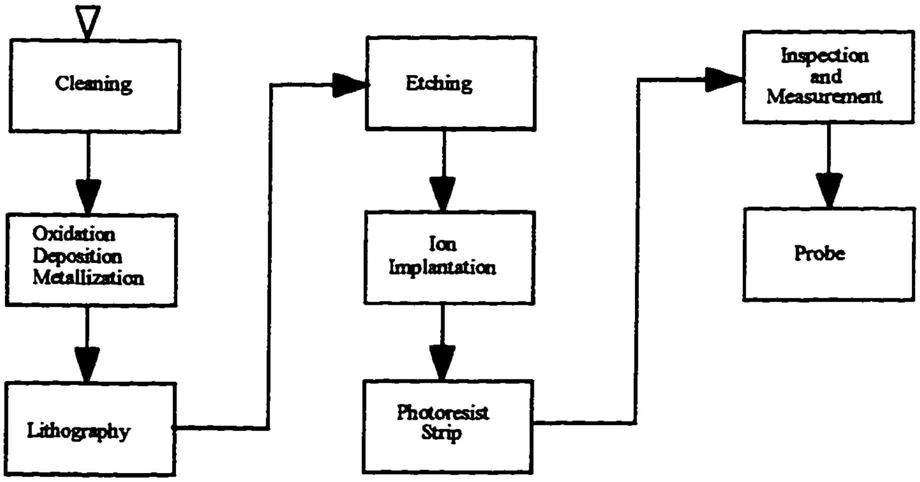

Figure 3-1: Basic Operation Sequence for Wafer Fabrication
Source: Uzsoy et al. (1992)

Depending upon the specific device family, there are typically between one hundred and two hundred operations required in the fabrication process. The impurities found in the raw materials used in the transformation process are measured in parts per billion. Each step in the process has been carefully devised to produce features with the minimum possible variance from specifications. The results of this exacting process are spectacular. Devices are produced containing hundreds of transistors that can fit on a pin head and cost only a few dollars.

The fabrication of integrated circuits requires the execution of a large number of individual complex interrelated operations. The process begins with growing of silicon crystals that are later thin sliced into wafers. These wafers are lapped to give them a highly polished surface. The wafers go through a number of carefully controlled processing steps, many of which are repeated. After completing all these complex operations, each wafer will yield hundreds of integrated circuit devices which are electrically tested and encapsulated in plastic molds.

Typically, integrated circuit fabrication steps can be grouped into five general types of processes: crystal growth, imaging, etching, deposition, and diffusion. The following sections shall describe these processes in more detail.

3.1.1. Crystal Growth Process

The parent material for all integrated circuit devices is silicon. This material is a grayness colored, semiconductive material. But before raw silicon can be utilized as a base stock, it must be processed into a purified, single crystal wafer.

The process starts with raw silicon which is purified and sent to "crystal growth." In crystal growth the raw silicon material is heated to a liquid state, and the impurities are separated from the chemically pure polycrystalline silicon. This purified silicon is then converted into a single-crystal ingot.

After the ingot is produced, it is sliced into wafers of thickness between 20 and 40 mils. These wafers are then lapped and polished to obtain a high quality surface. The final stage of this process is the chemical etching of the silicon wafer. This etching both removes contaminates and produces a surface of optical quality.

3.1.2. Imaging Processes

The imaging process replicates the integrated circuit pattern onto the wafer surface. This process is repeated several times during the transformation process. Careful control and monitoring of the process and the environment are extremely important.

The first step in this process is to pretreat the wafers. The wafers are chemically and mechanically cleaned to remove contaminates. After being force-dried and baked, the wafers are applied with a resist adhesion promoter. Next, they are coated with a photoresistant material and softbaked to remove any residual solvents remaining from the coating process.

The coated wafers are then exposed (similar to the film in your camera when taking a picture), transmitting the necessary pattern onto the surface of the wafer. Exposed wafers are developed, cleaned and then baked again to insure proper resist bonding. Unexposed resist materials are then removed from the wafer to expose the underlying semiconductive materials. The wafers are then placed into an acid etch process to remove semiconductive materials in the exposed regions.

3.1.3. Etching/Masking Processes

This operation performs the selective removal of silicon or non-conductive material. Undoped and doped silicon-dioxide, polysilicon, and aluminum etching are some of the common examples of the etching operation. There are two types of etching processes: wet and dry. Wet etching involves the submersion of the wafer into an acid bath for a predetermined period of time. The acid etches away the unmasked areas of the wafer, leaving channels for the deposition of selective conductive materials.

Plasma etching is a process in which a chemical layer is etched from the substrate by a highly reactive ionized gas (Rietman and Lory, 1993). It is possible to perform different chemical reactions with this process without exposing the reacting surfaces to high temperatures. Plasma etching is also called "dry etching."

Care must be taken that the etchants do not attack the pattern forming resist. Furthermore, etchant concentration has to be properly controlled to avoid either too much or too little etching.

3.1.4. Deposition Process

After the etching process conductive materials need to be deposited into the etched pathways in the wafer. These conductive materials form the transistors and connecting circuitry for the device. Typical materials used for deposition are barium, boron, and arsenic. This deposition of materials onto the wafer is accomplished by the bombardment of the deposition material with ions, thus sputtering the material onto the wafer. For the application of aluminum metalization to the wafer, an ohmic contact method is utilized. Another type of deposition process is epitaxy. In this process, a deposition of a dopant is applied to the wafer's silicon surface prior to diffusion. After deposition, the wafers are usually imaged and etched again.

3.1.5. Diffusion Process

This area in most integrated circuit facilities is human-operated with a minor degree of automation. Diffusion, in a classical sense, is the uniform distribution of particles within a fixed volume of space according to a physical mechanism that begins with the same particles in a concentrated state in the same fixed volume. The integrated circuit analog of this processes the thermally induced distribution of impurity atoms through the silicon crystal lattice structure of the wafer, thereby changing the electrical characteristics of the silicon. In this process, the diffusion of several elements simultaneously is common. There are two major steps in the diffusion process: predeposition and diffusion.

The objective of predeposition is to introduce a specific amount of dopant into the wafers' surface. This begins by first cleaning the surface to remove contaminates that might enter into the crystal structure. After the cleaning process, the wafers are loaded into a quartz boat or carrier and placed into a predeposition furnace. The dopant is then introduced into the furnace in either a solid, liquid, or gaseous state. As the heated dopant passes across the wafer surfaces, diffusion begins to take place. The diffusion rate of the dopants are temperature dependent. Increased temperatures will accelerate the movement of dopant atoms, permitting them to penetrate the wafer surface faster. Commonly used dopants are boron, phosphorus, arsenic, gallium, aluminum, gold and antimony (Elliot, 1982). As the dopants pass over the wafers in the predeposition furnace, the heated wafers become surface saturated with the dopant.

After predeposition, the dopants are driven to their final depth into the device structure in a diffusion furnace with an ambient oxygen, or oxidizing atmosphere, and no additional dopant is added. In the oxidizing environment, a silicon dioxide layer is grown over the newly diffused areas. The only areas not diffused are those previously protected by silicone dioxide. These layers of silicon dioxide are generally one micrometer in thickness, and they prevent the dopant from penetrating into unwanted areas of the device.

3.2. Process Flow of the Typical IC Fabrication Process

In a process layout, or job-shop layout, similar equipment or functions are grouped together. Even though this type of layout is typically a characteristic of low-volume manufacturing, it is utilized in the production of semiconductor devices. In the production of integrated circuits, it is not uncommon for the product unit (wafer) to be routed through the same processing equipment numerous times. Semiconductor wafer fabrication can be characterized as a multi-stage process with reentrant flows (Gurnani et al., 1992). There are two basic types of machines utilized in the processing of wafers: fab-serial machines which process one wafer at a time and batch machines which work on multiple wafer/lots. In this research, we regard the setup load of the fab-serial machines as that resource's capacity instead of the single unit it processes. An example of this is the stepper. This piece of equipment is used to photograph, expose, the wafer with the integrated circuit pattern. The exposing process is performed one wafer at a time, but the setup load for the machine is 24 units. Thus the processing capacity is considered 24 units. Figure 3-2 shows a generic layout of a front-end operation. Figure 3-3 illustrates the structure of the process flow in a typical wafer fab.

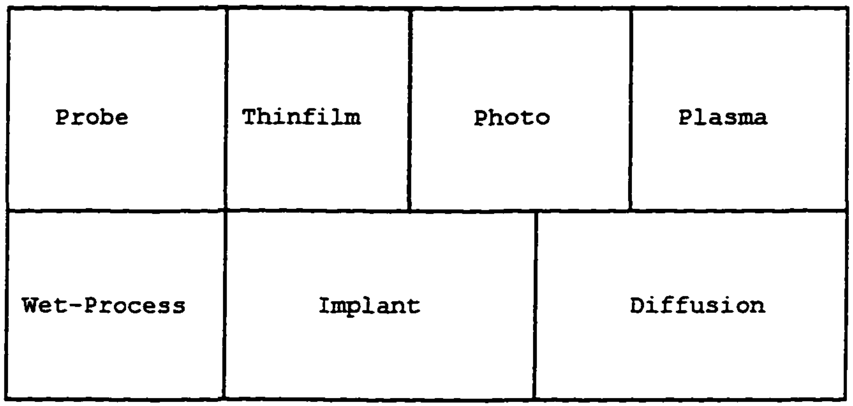

Figure 3-2: Generic Wafer Fab Shop Layout

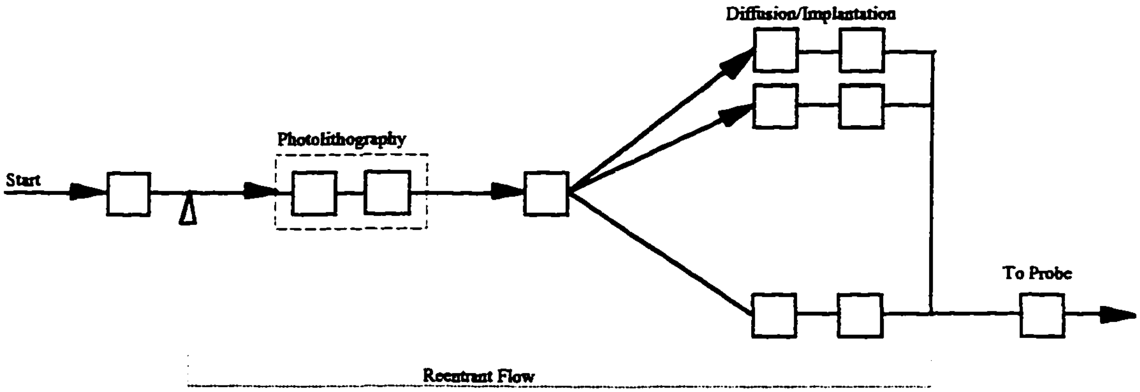

Figure 3-3: Generic Wafer Fab Process Flow
Source: Gurnani et al. (1992)

It is also characteristic of this type of production process that there are several different type of machines in each of these areas. Appendix A provides a listing of these machines and the areas that they are found in. The exact number of each type machine will vary from facility to facility dependent upon the types of product and the production volume.

In many semiconductor fabrication operations, it is not unusual to have upwards to a hundred different product types be produced in a given demand period. As a general indicator of capacity, the average daily demand per product type is about 10 wafers, and the average total daily demand is about 850 wafers. The typical process yields per product type will range between 92 and 99 percent. The typical number of processing steps in a given product type can be as many as 200. Some experimental products have had as many as 750 processing steps. The processing requirements of these three products will be utilized in the simulation described in Chapter 5.

3.3. Summary

The fabrication of integrated circuits is one of the most complicated manufacturing processes in existence. It is characterized by both its batch processing technique and its job shop environment. This chapter has presented only an overview of the typical operations and processing that occur in the fabrication of an integrated circuit. The next chapter shall discuss the research methodology that will be applied to investigate and solve the lot sizing problem described in Chapter 1 and discussed in Chapter 2.

CHAPTER 4

RESEARCH METHODOLOGY

In the previous chapter, a discussion of the manufacturing process of interest was presented. In this chapter, a research methodology is described. The chapter will begin with a survey of possible methodologies and then synthesize from that an appropriate plan for the conduct of this research.

4.1. Research Methodologies for Production and Operations Management

According to Mason (1988), the different methods of inquiry are: mathematical and logical models, computer simulations, laboratory experiment, field experiment, survey research, field studies, case research, and personal reports. The trade-off between tightness of control and realism progress from low realism, high control in the mathematical models to high realism, low control in the personal reports. In designing an experiment, the researcher wants to choose the method of inquiry that will provide both the highest degree of realism and control as possible.

4.1.1. The Stages of Research

Meredith et al., (1989) suggested that there are three research tasks: description, prediction, and explanation. They also suggested that all research activities should involve a continuous repetitive cycle of description, explanation, and testing. Figure 4-1 illustrated their idea.

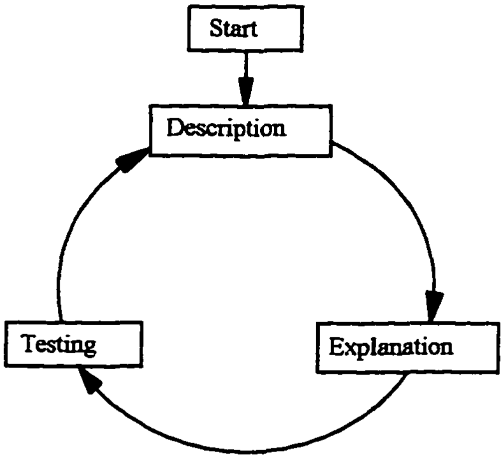

Figure 4-1: The Ongoing Cycle of Research Stages
Source: Meredith et al., (1989)

Flynn et al., (1990) present a five stage approach to research. This approach is empirical in nature, thus can help provide a stronger tie to real-world applications. The stages of Flynn's method are: (1) establish the theoretical foundation for the research, (2) develop the research design, (3) data collection, (4) data analysis, and (5) preparing the research report. Figure 4-2 illustrates this approach to research.

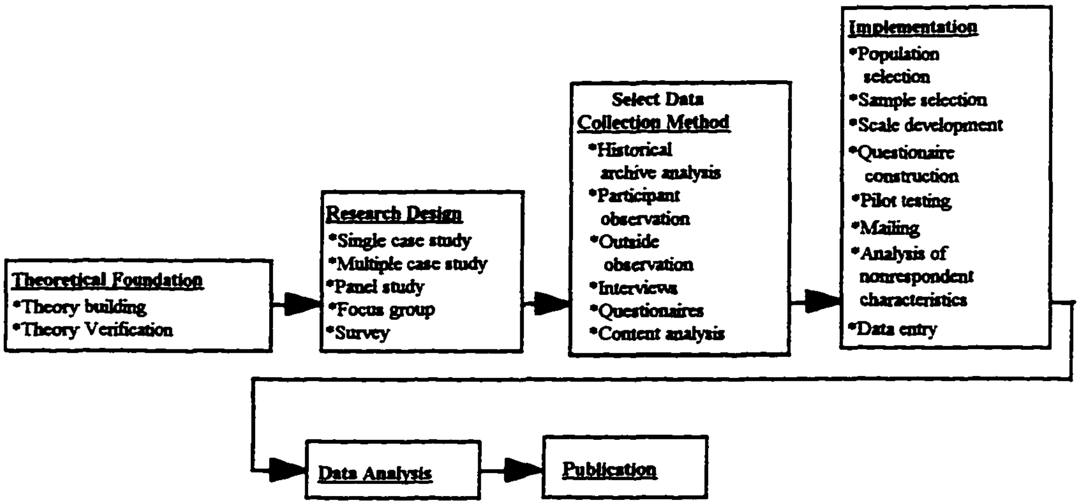

Figure 4-2: A Systematic Approach for Empirical Research
Source: Flynn et al., (1990)

Baldwin and Yadav (1995) present a unified view of research methods. Though their focus was on artificial intelligence, there is some commonality in the basic approach with the two previous methodologies. In their work, Baldwin and Yadav define two levels for the describing of a system: the knowledge level and the symbol level. According to Baldwin and Yadav (1995) the knowledge level description of a system is the beliefs, goals, reasoning capabilities, learning capabilities, and potential actions that are attributed to a system so that its behavior can be understood. Baldwin and Yadav (1995) also describe the symbol level description of a system is the internal architecture or representation of an architecture that is used to create and represent the knowledge level.

The unified methodology consists of nine steps that can be grouped into three stages. These steps are to: (1) formulate the problem, (2) construct knowledge-level principles or theories that address the problem, (3) construct symbol-level theories or principles, (4) operationalize knowledge level theories in terms instances, and form hypotheses, (5) identify or construct a symbol-level designs and form symbol oriented hypotheses, (6) identify or develop prototype systems based upon the above design, (7) test the system, (8) evaluate and validate the results, and (9) refine the problem, theories, principles, and hypotheses, and then repeat steps 1-8, if necessary. Table 4-1 contrasts these methodologies.

4.1.2. Dimensions of Research Methods

There are several dimensions, or methods, by which research can be classified. This classification could be related to the data collection technique utilized by the researcher: model, literature, survey, observation, interview, experiment, laboratory, etc. (Meredith et al., 1989). The classification could also be based upon the data analysis method: statistical, protocol analysis, taxonomy (Meredith et al., 1989). Another method of classifying research is according to the immediate purpose of the research: exploration, description, evaluation, hypotheses generation, hypothesis testing (Meredith et al., 1989).

Table 4-1: Comparison of Research Methodologies
Source: Baldwin and Yadav (1995)

Classical Scientific Method	Ackoff's General Research Methodology	Meredith et al., Method	Flynn et al., Method	Unified Method
Problem Formation		Description Stage		
• Observe	• Formulate Problem	• Observe and report and chronicle elements of situation		• Formulate problem
Theory Building		Explanation Stage		
• Develop theory	• Develop model of proposed solution	• Develop a conceptual framework • Develop theory on the principles operating in the situation	• Establish theoretical Foundation	• Develop knowledge level theory • Develop symbol level theory
Theory Testing		Testing Stage		
• Develop hypotheses	• Develop operational system based on model			• Operationalize knowledge level and develop instances and hypotheses • Construct symbol level design and form symbol level hypotheses
• Create Experiment		• Make a prediction	• Select research design	• Identify or develop prototype system
• Data collection	• Test the system	• Make observations on prediction	• Data collection	• Test system
			• Implementation	
• Data analysis	• Evaluate and validate results		• Data Analysis	• Evaluate and Validate results
• Modify theories and repeat steps	• Refine model and repeat	• repeat as required	• Publication of Findings	• Modify problem and theories and repeat

Mitroff and Mason specify two dimensions as being key to shaping the philosophical basis for research activities (Meredith et al., 1989). These dimensions are natural/artificial and rational/existential. The rational/existential dimension focuses on the nature or truth and its independence from the human experience. The natural/artificial dimension focuses upon the source and type of information used in the research. Figure 4-3 presents these two dimensions and methodologies available for each of the associated perspectives.

Natural ↔ Artificial

Rational ↕ Existential

	Direct Observation of Object Reality	People's Perceptions of Object Reality	Artificial Reconstruction of Object Reality
Axiomatic			•Reason/Logic/ Theorems •Normative Modeling •Descriptive Modeling
Logical Positivist/ Empericist	•Field Study •Field Experiment	•Structured Interviewing •Survey Research	•Prototyping •Physical Modeling •Laboratory Experiment •Simulation
Interpretive	•Action Research •Case Studies	•Historical Analysis •Delphi •Intensive Interviewing •Expert Panels •Futures/Scearios	•Conceptual Modeling •Hermeneutics
Critical Theory		•Introspective Reflection	

Figure 4-3: A Framework for Research Methods
Source: Meredith et al., (1989)

4.1.2.1. The Rational/Existial Dimension. This dimension focuses upon the cognitive structure of the research process, and involves the benefits and limitations of the approach taken for generating the knowledge. There are four generic perspectives in this dimension: axiomatic, logical positivist, empiricist, interpretive, and critical

(Meredith et al., 1989). These perspectives structure the research with different degrees of formality.

According to Meredith et al., the axiomatic perspective uses the theorem-proof structure. The logical positivist/empiricist perspective views the phenomenon under study as being isolated from its environment. It also assumes that the observations are independent of the laws and theories that are used to explain them. The interpretive perspective looks at both the phenomenon and its environment. The critical perspective attempts to synthesize the positivist and interpretive perspectives and get past the dichotomies by looking at the broader context.

4.1.2.2. The Natural/Artificial Dimension This dimension is concerned with the source and kind of information used in the research. In this dimension the mechanisms used in the study mold the researcher's perception of reality (Meredith et al., 1989). Meredith et al., define three categories for this dimension: object reality, people's perceptions of object reality, and artificial reconstruction of object reality.

Meredith et al., define object reality as referring to the direct observations by the researcher of the phenomenon. Artificial reconstruction of object reality is research that is performed using analytic models, computer simulations, or information constructs.

4.2. The Research Methodology

Table 4-1 provides us a comparison of the research methodologies reviewed in the chapter. In section 4.2.1, the theoretical foundation for this research will be presented. Section 4.2.2 shall provide a synopses of the problem description made in Chapters 1, 2, and 3. Sections 4.2.3 and 4.2.4 shall, respectively, discuss the plan for explaining and testing the problem of interest.

"A research paradigm is a set of methods that all exhibit the same pattern or element in common. However, there are a number of dimensions on which research activity may be classified" (Meredith et al., 1989, p. 305). The development of the analytical constructs in this research is exploratory in nature, and will utilize both inductive and deductive methods of inquiry. The evaluation and verification of these constructs, utilizing a simulation model, will confirm the validity of these constructs as a reasonable representation of the process being evaluated. The research methodology utilized in this research falls into the natural/artificial dimension.

Meredith et al. (1989) describes three categories into which the mechanism of the researchers perception of reality could be classified: object reality, people's perceptions of object reality, and artificial reconstruction of the phenomenon. This research utilizes all three of these mechanisms. The object reality perception is based upon personal work experience in the semiconductor industry, and other job-shop related in industries. The people's perceptions of object reality is based upon interviews, direct review, and support from professionals currently employed in the semiconductor industry (specifically, Texas Instruments, Inc.) who are interested in this research. The and artificial reconstruction of the phenomenon is based upon the analytical modeling of the production process under investigation, and the simulating of that process.

As previously stated, Mason (1988) maintains that the different methods of inquiry are: mathematical and logical models, computer simulations, laboratory experiment, field experiment, survey research, field studies, case research, and personal reports. The trade-off between tightness of control and realism progress from low realism, high control in the mathematical models to high realism, low control in the personal reports. In designing an experiment, the researcher wants to choose the method of inquiry that will provide both the highest degree of realism and control as possible. To accomplish both the highest degree of realism and control, this research will utilize the three perceptual mechanisms discussed in the previous paragraph: analytical modeling, simulation, and object reality.

Using the methodology proposed by Meredith et al., (1989), this research shall progress with a description stage, then an explanation stage, followed by a testing stage. The description stage of this research has already been presented in Chapters 1 and 2. The explanation stage of this research shall develop the theoretical framework of the problem. Finally, the testing stage shall define the methodology that this research will use in validating the model developed in the explanation stage.

4.2.1. Theoretical Foundation

The theory behind the research problem being studied by this thesis is that operational policies will affect the production process' ability to meet strategic objectives. Because lot size is not a fixed variable based upon the design of the production process, it can be determined or changed by the operational policies of management. Thus, it can be hypothesized that lot size will affect the production process' ability to meet strategic objectives. It can further be hypothesized that as the production process' ability to meet strategic objectives diminishes, the firms net profits will diminish. If these hypotheses are true then it can be further hypothesized that for each product type, given a predetermined set of production parameters, that there exists an optimal lot size.

4.2.2. The Description Stage

"Problem formulation includes the search for issues, formulation of research objectives, analysis of previous research and creation of a problem statement" (Baldwin and Yadav, 1995, p. 855). The problem addressed by this research has as its focus the effect of production lot sizing on the production system, specifically on net profits, and is presented fully in section 1.2. This issue is a common one that is faced daily by operation managers. The decision to use one lot size versus another, and whether or not to maintain lot integrity, will impact production costs, product holding costs, setup costs, and cycle time. This problem is further complicated by increases in the number of products being produced and the number of operating steps in the process.

Chapter 2 of this proposal reviews the current literature associated with the production planning and control problem of determining the optimal lot size. Goldratt's theory of constraints has been shown by several researchers (Wu et al., 1994; Glassey and Resende, 1988; Wein, 1988) as providing the best production control framework of all the current shop floor control methods. The practice of lot streaming has also been found to provide better utilization of production resources, as well as, reducing product cycle times (Goldratt and Fox, 1986; Goldratt, 1980; Fox, 1983; Kulonda, 1984; Baker and Pike, 1990; Trietsch, 1987; Baker, 1987; Trietsch and Baker, 1993; Potts and Baker, 1989; Campbell et al., 1970; Potts and Van Wassenhove, 1992). The work of Baker and Pyke (1990) showed that even though there are many good algorithms for determining sublot sizes, that there are no efficient optimization procedures for the m machine case.

From the literature review in Chapter 2, none of the lot sizing models found considered all of the elements present in the production process. Many authors considered setups, some authors considered process quality or yield rate, others have considered bottlenecks. There are even a few models that consider various constraints such as budgets or machine availability, but none of the models considered all of these aspects. And, with the exception of some of the simulations, none of them considered resource load capacities. The work presented in this dissertation presents a model that incorporates all of these aspects of the production environment, except for machine availability. Based upon the theory of constraints, where the only resource that is necessary to consider availability is the bottleneck, it is felt that machine availability can be overlooked as long as the throughput of the bottleneck is calculated based solely upon the available production of the bottleneck.

As mentioned earlier, the procedure presented by Goldratt (1980) provides the best shop floor control methodology. In this procedure, three lot sizes are utilized: the process batch, the transfer lot, and the control lot. EOQ based models, or even discrete demand-based scheduling programs such as MRP, provide an adequate determination of the process batch. Goldratt outlines his procedure for determining transfer lot sizes at each phase of the production cycle, but he does not present a method for determining the control lot size.

The need for lot traceability is based upon three factors: the legal environment, the customer, and management. In an environment where there is no need to trace a production lot through the transformation cycle, the determination of the control lot's size is probably a moot issue. In this case, the lot could be unbatched and batched as required to optimize the utilization of each resource in the production line.

Where lot traceability is deemed desirable, the lot cannot be divided and rebatched as needed without loss of tracking data. To determine the optimal size of the control lot, based upon the maximization of net profits, a model needs to be developed that considers all of the production factors discussed earlier. The theoretical development of a model for this purpose shall be presented in the explanation stage of this research.

4.2.3. The Explanation Stage

By determining and utilizing the optimal lot size, the firm will maximize its net profits with respect to the overall contribution to profits made by the production function of the firm. Based upon personal experience, information provided by practicing industry professionals, and previous research (refer to Chapter 2), an analytical model shall be developed that explains the relationships between lot size production costs, holding costs, setup costs, gross revenues, and net profits. The primary variables used in the model to describe these relationships are: lot size, resource load capacities, process yield, product demand, the number of processing operations, and bottleneck location. Chapter 5 fully develops the theoretical model that will maximize net profits by determining the optimal lot size for each product in the production process.

The basic format of this model is based upon the EOQ model, more specifically Hum and Sarin's (1191) model in Equation 2-5. The premise for this format lies in Goldratt and Fox's (1986) definition of net profits. They defined net profits[1] as the difference between throughput[2] and operating expenses. The model presented by the Hum and Sarin (reference Eqn. 2-5) is consistent with this definition.

4.2.4. The Testing Stage

The final stage of the research methodology is to test the concepts developed in the previous stage to determine if they are correct. The model (reference Eqn. 5-30) developed in the explanation stage of this research shall be tested using a simulation of the typical wafer fab. Where possible

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[1] In this research "net profits" are defined as gross revenues less the sum of all costs (expenses).

[2] In this research "throughput" is used synonymously with process output as measured in finished, defect free, production units. As such, to be compatible with Goldratt's definition our usage of throughput must be multiplied by the market price of the given product type.

the theorized revenue and cost equations developed in Chapter 5 will be compared with historical production data. The simulation model shall also be build to validate the results of the model developed in Chapter 5.

4.2.4.1. Testing the Model Through Simulation. The primary testing methodology for this research is to utilize a simulation model. The simulation to be built will be representative of the typical wafer fab. The material release policy utilized shall be the workload regulating input policy. Simulation work on wafer fab shop control systems performed by Wein (1988) found this policy yielded the best overall performance. The prioritization rule for lot sequencing and selection at each queue point within the process shall be the first-in-first-out rule. The usage of this prioritization rule is supported by research from Glassey and Rosende (1988) and Wein (1988). To validate the production lot sizing model results, iterative runs of the simulation shall be made starting with the largest feasible lot size and decreasing by one unit with each iteration.

4.2.4.2. Iteration. As illustrated in Figure 4-1, it is anticipated that minor adjustments may have to be made to the analytical model. As corrections are implemented, a new series of simulation runs will be conducted. This process will be repeated until there is a reasonable level of agreement between the analytical model and the simulation. Corrections to the analytical and the simulation models may also be made based upon results from the data analyses.

4.3. Summary

In all of the methodologies reviewed in this chapter, the basic approach to performing research is similar. All of the methods start with observing a situation and formulating a problem statement. Once the problem has been described, a theory or framework must be developed for the situation. This theory should explain the situation, thus providing a foundation for the designing of an experiment or the development of a hypothesis. Finally, the hypothesis needs to be tested. Though the language of the reviewed methodologies differ slightly, all of them are compatible.

This research is exploratory in nature, and will utilize both inductive and deductive methods of inquiry. The research methodology to be utilized in this study is a synthesis of the above reviewed methodologies. Chapters 1 and 2 have described the research problem of interest. Chapter 3 provided some of the basic environmental details in which the research problem is to be studied. Chapter 5 will provide the analytical explanation for the problem. This explanation will consist of both a discussion of the theorized relationships associated with this problem and the development of an analytical model for making predictions. Chapter 6 shall discuss the production data collected from Texas Instruments, Inc., and the construction of the simulation. Chapter 7 shall develop the validation strategy and present the results of the validating analysis.

CHAPTER 5

DEVELOPMENT OF THE THEORIZED MODEL

In the previous chapters, a problem was identified in that there were not good models for determining the optimal production lot size in the n job, m machine, job shop. Literature was reviewed regarding this problem, and a research methodology was identified for the investigation of this problem. This chapter shall develop an analytical model for solving this problem.

5.1. Introduction

Firms working in the production environment throughout most of this century produced finished goods that were stored in inventory until sold to the customer. In the current business environment, where speed and flexibility are key competitive factors, maintaining large inventories is unacceptable. If a firm's product cycle time is too long, it will lose customers. If they hold finished goods too long, there is a risk of loss and obsolescence. There is also an opportunity cost associated with having large amounts of capital tied up in inventories instead of being able to invest it in profit-generating activities. Accountants amass all such costs into a holding cost (H).

The trend in manufacturing has been to transition away from produce-to-stock strategies to produce-to-order and engineer-to-order strategies that curtail overhead costs, especially for finished inventory. In order to support organizational goals, the operations manager faces the decision of what lot size will minimize cycle times and maximize net profits. The primary variables in traditional EPQ-based models are annual demand, production capacity, setup costs, and overhead costs.

Goldratt (1990, p. 55) said that

> as long as the goal of our company is to make money now as well as in the future, financial measurements are essential ... Dropping cost accounting will leave us without a numerical way to judge many types of decisions ... Every measurement must, by definition, have the dollar sign in it.

In the development of a production lot sizing (PLS) model, the variables of demand, production costs, overhead costs, and setup costs shall be analyzed and defined in terms of process quality (as a measure of the cost of quality), load capacities, and product cycle time. This development will proceed from the explicit assertion of the assumptions given in Chapter 1.

5.2. Description of the Multistage Production Problem

In the flow shop environment lots are processed on machines 1,...,m. The process routing of lots through these machines typically occurs in the same sequence. In cases like with integrated circuit fabrication, a lot may be processed through the same machine numerous times in the transformation process. This case is discussed in section 3.2. Each machine i may have a different processing capacity (Ψ_{ij}), depending on the product j.

There are multiple product families k, and multiple product models j. In the development of the following model, only one family of product is considered, and within the same product model, all lot sizes are assumed equal (Q_j). Given the product model j, each machine i may have a different processing time (τ_{pij}). Depending upon the size of the lot and the machine's processing capacity, each machine may process multiple lots simultaneously. The restriction on this multiple lot processing is that lots are not allowed to be split, even if there is remaining capacity in the machine.

At the start of k^{th} product, a major setup of the production line is required. No major setup is required between lots belonging to the same family. Additionally, a minor setup is required between process runs of lots irrespective of model type.

Table 5-1 details a five-step process that will be utilized in the development of the relationships between lot size and (1) process yield, (2) production costs, (3) overhead costs, and (4) setup costs. The relationships developed from this problem will be externally validated, in the next two chapters, from data collected from Texas Instruments, Incorporated, and by use of a simulation model.

Table 5-1: The Five Step Production Problem

	Process Time (t_i)	Process Cost/hr (C_i+L)	Process Setup Cost	Lot Setup Cost	Capacity per run	Annual Capacity	Setup Time (t_S)
Resource A =	9.1E-05	$5.00	$ 150.00	$ 3.00	45	412500	0.1
Resource B =	1.8E-04	$4.50	$ 75.00	$ 2.70	50	252294	0.09
Resource C =	2.3E-04	$4.25	$ 300.00	$ 2.25	40	166038	0.075
Resource D =	1.4E-04	$5.00	$ 250.00	$ 3.00	50	323529	0.1
Resource E =	9.1E-05	$5.75	$ 50.00	$ 3.60	55	487903	0.12
Sums:	0.000727		$ 825.00	$14.55			0.485

$R_{(ext\ constraint)}$ =163,964	Days /Year (N) = 250	t_P= 0.000915	t_S= 1.36E-05
$R_{(int\ constraint)}$ =166,038	Hours / Day = 22		M = $ 4.50
p =166,038	Labor Rate/hour = $ 30.00	n = 5	t_{ct} = 0.001307
material cost = $ 1.50	y = 0.9974	g= 3	
Prod. Cost/lot = $ 18.94			

5.3. Propositions

The development of the theorized model of this chapter is based upon four propositions. The premise of these propositions is focused upon the concept of load capacity utilization. Load capacity utilization can be defined as the average percentage of the total machine load capacity that is used per production run. An example of this concept can be made as follows: given the assumptions stated in section 5.1, load capacity utilization is maximized when the number of production units represented by the product lot size and the number of lots being processed at a given resource is equal to the total load capacity of that resource. Thus, it can be seen that when the lot size is equal to the total load capacity of a given resource, only one lot of material can be processed and the load capacity utilization is 100%. As the lot size decreases, the load capacity utilization will decrease until the point at which lot size is one half of the total load capacity of that resource and two lots can be processed. At that point the load capacity utilization is again 100%. Figure 5-1 illustrates this concept.

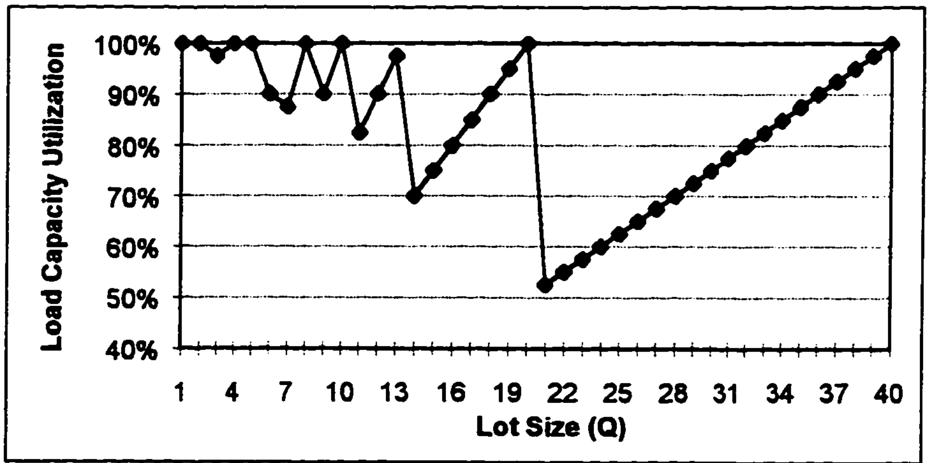


Figure 5-1: Load Capacity Utilization of a 40-unit Capacity Machine

Based upon this concept of load capacity utilization the following propositions can be made:

Proposition 1: As load capacity utilization decreases, system output will decrease.

Proposition 2: As load capacity utilization decreases, production costs will increase.

Proposition 3: As load capacity utilization decreases, setup costs will increase.

Proposition 1 directly relates to the management of the bottleneck. Propositions 2 and 3 relate to all of the processing activities that occur in the production system. In all three of these propositions, as fewer production units are being simultaneously processed at a given operation, the utilization of that operation will diminish. This diminishing utilization will cause the production cost per unit to increase, the system output of the operation will decrease, and the number of setups will increase. Again, these three propositions are based upon the affect of working with fewer production units at a given operation than that operation is capable of handling.

The next proposition is not directly related to load capacity utilization, but does affect the overall performance of the production system.

Proposition 4: Up to the point where the production system starts shutting down, as cycle time increases, overhead costs will increase.

5.4. Revenue Generation

The basis of revenue generation is being able to deliver a quality product to the market place that customers want and are willing to pay for, in a timely fashion. As shown in section 5.2, the number of production units that can be moved through the production system is significantly affected by lot size. Thus, as load capacity utilization increases the system output of the system will increase. Finally, by considering the yield of the process, while maintaining lot integrity, the system output for the j^{th} product can be modeled as follows:

$$T_j = Y_j D_j \left(\frac{\eta_{bj} Q_j}{\Psi_{bj}} \right) \quad \text{s.t. } T_j \leq \text{max. system output} \qquad \text{Eqn. 5-1}$$

where, Y_j is the process yield for the j^{th} product, D_j is the period demand for the j^{th} product, η_{bj} is the number of lots that the bottleneck for the j^{th} product can simultaneously process, Ψ_{bj} is the load capacity of the j^{th} product's bottleneck, Q_j is the lot size for the j^{th} product, and if $D_j <<$ max. system output, then $D_j \left(\frac{\eta_{bj} Q_j}{\Psi_{bj}} \right) \cong D_j$. The material release schedule for the j^{th} product is assumed to be equivalent to the demand for the period divided by the total number of releases for the period, such that the total releases do not exceed the maximum production capabilities of the j^{th} process. By multiplying the system output of each product that the firm produces by the market price for each respective product, the total revenues of the system, for the demand period, can be calculated as follows,

$$\mathrm{R} = \sum_{j=1}^{k} M_j T_j \qquad \text{Eqn. 5-2}$$

where, and M_j is the market price of the j^{th} product.

From literature, it is expected that as the cycle time for a product decreases that either, or both, the demand for the product would increase or the market price could be increased. Using Table 5-1 and the queuing theory model for waiting time in the system for an automated process, Table 5-2 will calculate the expected time in the system at each processing operation, at each lot size starting at forty units per lot and going down to one unit per lot. From these calculations, the expected cycle time of the five step process described in Table 5-1 will be determined.

Table 5-2: Expected Cycle Times for the Production Problem

Demand =	166000	Process Step 1			Process Step 2			Process Step 3			Process Step 4			Process Step 5				
Lot Size	Release	$\psi 1=45$	$\tau 1=.5$	s=0	$\psi 2=50$	$\tau 2=1$	s=0	$\psi 3=40$	$\tau 3$	s=0	$\psi 4=50$	$\tau 4=.75$	s=0	$\psi 5=55$	$\tau 5=.5$	s=0		
(Q)	Rate lots/hr	arvl1	$\mu 1$	$E(\lambda 1)$	arvl2	$\mu 2$	$E(\lambda 2)$	arvl3	$\mu 3$	$E(\lambda 3)$	arvl4	$\mu 4$	$E(\lambda 4)$	arvl5	$\mu 5$	$E(\lambda 5)$	$E(\lambda)$ in hrs	Std $E(\lambda)$
1.0	30.18	30.2	90.0	0.0	30.2	50.0	0.0	30.2	32.00	0.3	30.2	66.7	0.0	30.2	110.0	0.0	0.4	0.01
2.0	15.09	15.1	44.0	0.0	15.1	25.0	0.1	15.1	16.00	0.6	15.1	33.3	0.0	15.1	54.0	0.0	0.7	0.02
3.0	10.06	10.1	30.0	0.0	10.1	16.0	0.1	10.1	10.40	1.5	10.1	21.3	0.1	10.1	36.0	0.0	1.8	0.05
4.0	7.55	7.5	22.0	0.1	7.5	12.0	0.2	7.5	8.00	1.2	7.5	16.0	0.1	7.5	26.0	0.0	1.6	0.04
5.0	6.04	6.0	18.0	0.1	6.0	10.0	0.2	6.0	6.40	1.5	6.0	13.3	0.1	6.0	22.0	0.1	1.9	0.06
6.0	4.70	4.7	14.0	0.1	4.7	8.0	0.2	4.7	4.80	5.3	4.7	10.7	0.1	4.7	18.0	0.1	5.8	0.16
7.0	3.92	3.9	12.0	0.1	3.9	7.0	0.2	3.9	4.00	6.4	3.9	9.3	0.1	3.9	14.0	0.1	6.9	0.19
8.0	3.77	3.8	10.0	0.1	3.8	6.0	0.3	3.8	4.00	2.3	3.8	8.0	0.2	3.8	12.0	0.1	3.0	0.09
9.0	3.14	3.1	10.0	0.1	3.1	5.0	0.4	3.1	3.20	8.0	3.1	6.7	0.2	3.1	12.0	0.1	8.8	0.24
10.0	3.02	3.0	8.0	0.2	3.0	5.0	0.4	3.0	3.20	2.9	3.0	6.7	0.2	3.0	10.0	0.1	3.8	0.10
11.0	2.35	2.4	8.0	0.2	2.4	4.0	0.4	2.4	2.40	10.6	2.4	5.3	0.3	2.4	10.0	0.1	11.8	0.31
12.0	2.35	2.4	6.0	0.2	2.4	4.0	0.4	2.4	2.40	10.6	2.4	5.3	0.3	2.4	8.0	0.2	11.7	0.31
13.0	2.32	2.3	6.0	0.2	2.3	3.0	0.9	2.3	2.40	6.6	2.3	4.0	0.4	2.3	8.0	0.2	8.3	0.22
14.0	1.67	1.6	6.0	0.2	1.6	3.0	0.5	1.6	1.60	15.9	1.6	4.0	0.3	1.6	6.0	0.2	17.2	0.46
15.0	1.67	1.6	6.0	0.2	1.6	3.0	0.5	1.6	1.60	15.9	1.6	4.0	0.3	1.6	6.0	0.2	17.2	0.46
16.0	1.67	1.6	4.0	0.3	1.6	3.0	0.5	1.6	1.60	15.9	1.6	4.0	0.3	1.6	6.0	0.2	17.3	0.46
17.0	1.67	1.6	4.0	0.3	1.6	2.0	1.4	1.6	1.60	15.9	1.6	2.7	0.6	1.6	6.0	0.2	18.6	0.50
18.0	1.67	1.6	4.0	0.3	1.6	2.0	1.4	1.6	1.60	15.9	1.6	2.7	0.6	1.6	6.0	0.2	18.6	0.50
19.0	1.67	1.6	4.0	0.3	1.6	2.0	1.4	1.6	1.60	15.9	1.6	2.7	0.6	1.6	4.0	0.3	18.6	0.50
20.0	1.61	1.6	4.0	0.3	1.5	2.0	1.3	1.5	1.60	5.8	1.5	2.7	0.6	1.5	4.0	0.3	8.4	0.22
21.0	0.78	0.8	4.0	0.3	0.8	2.0	0.7	0.8	0.80	31.9	0.8	2.7	0.6	0.8	4.0	0.3	33.6	0.90
22.0	0.78	0.8	4.0	0.3	0.8	2.0	0.7	0.8	0.80	31.9	0.8	2.7	0.6	0.8	4.0	0.3	33.6	0.90
23.0	0.78	0.8	2.0	0.7	0.8	2.0	0.7	0.8	0.80	31.9	0.8	2.7	0.6	0.8	4.0	0.3	33.9	0.91
24.0	0.78	0.8	2.0	0.7	0.8	2.0	0.7	0.8	0.80	31.9	0.8	2.7	0.6	0.8	4.0	0.3	33.9	0.91
25.0	0.78	0.8	2.0	0.7	0.8	2.0	0.7	0.8	0.80	31.9	0.8	2.7	0.6	0.8	4.0	0.3	33.9	0.91
26.0	0.78	0.8	2.0	0.7	0.8	1.0	2.8	0.8	0.80	31.9	0.8	1.3	1.3	0.8	4.0	0.3	36.9	0.99
27.0	0.78	0.8	2.0	0.7	0.8	1.0	2.8	0.8	0.80	31.9	0.8	1.3	1.3	0.8	4.0	0.3	36.9	0.99
28.0	0.78	0.8	2.0	0.7	0.8	1.0	2.8	0.8	0.80	31.9	0.8	1.3	1.3	0.8	2.0	0.7	37.3	1.00
29.0	0.78	0.8	2.0	0.7	0.8	1.0	2.8	0.8	0.80	31.9	0.8	1.3	1.3	0.8	2.0	0.7	37.3	1.00
30.0	0.78	0.8	2.0	0.7	0.8	1.0	2.8	0.8	0.80	31.9	0.8	1.3	1.3	0.8	2.0	0.7	37.3	1.00
31.0	0.78	0.8	2.0	0.7	0.8	1.0	2.8	0.8	0.80	31.9	0.8	1.3	1.3	0.8	2.0	0.7	37.3	1.00
32.0	0.78	0.8	2.0	0.7	0.8	1.0	2.8	0.8	0.80	31.9	0.8	1.3	1.3	0.8	2.0	0.7	37.3	1.00
33.0	0.78	0.8	2.0	0.7	0.8	1.0	2.8	0.8	0.80	31.9	0.8	1.3	1.3	0.8	2.0	0.7	37.3	1.00
34.0	0.78	0.8	2.0	0.7	0.8	1.0	2.8	0.8	0.80	31.9	0.8	1.3	1.3	0.8	2.0	0.7	37.3	1.00
35.0	0.78	0.8	2.0	0.7	0.8	1.0	2.8	0.8	0.80	31.9	0.8	1.3	1.3	0.8	2.0	0.7	37.3	1.00
36.0	0.78	0.8	2.0	0.7	0.8	1.0	2.8	0.8	0.80	31.9	0.8	1.3	1.3	0.8	2.0	0.7	37.3	1.00
37.0	0.78	0.8	2.0	0.7	0.8	1.0	2.8	0.8	0.80	31.9	0.8	1.3	1.3	0.8	2.0	0.7	37.3	1.00
38.0	0.78	0.8	2.0	0.7	0.8	1.0	2.8	0.8	0.80	31.9	0.8	1.3	1.3	0.8	2.0	0.7	37.3	1.00
39.0	0.77	0.8	2.0	0.7	0.8	1.0	2.7	0.8	0.80	19.8	0.8	1.3	1.3	0.8	2.0	0.7	28.1	0.87
40.0	0.75	0.8	2.0	0.7	0.8	1.0	2.5	0.8	0.80	11.6	0.8	1.3	1.2	0.8	2.0	0.7	18.7	0.46

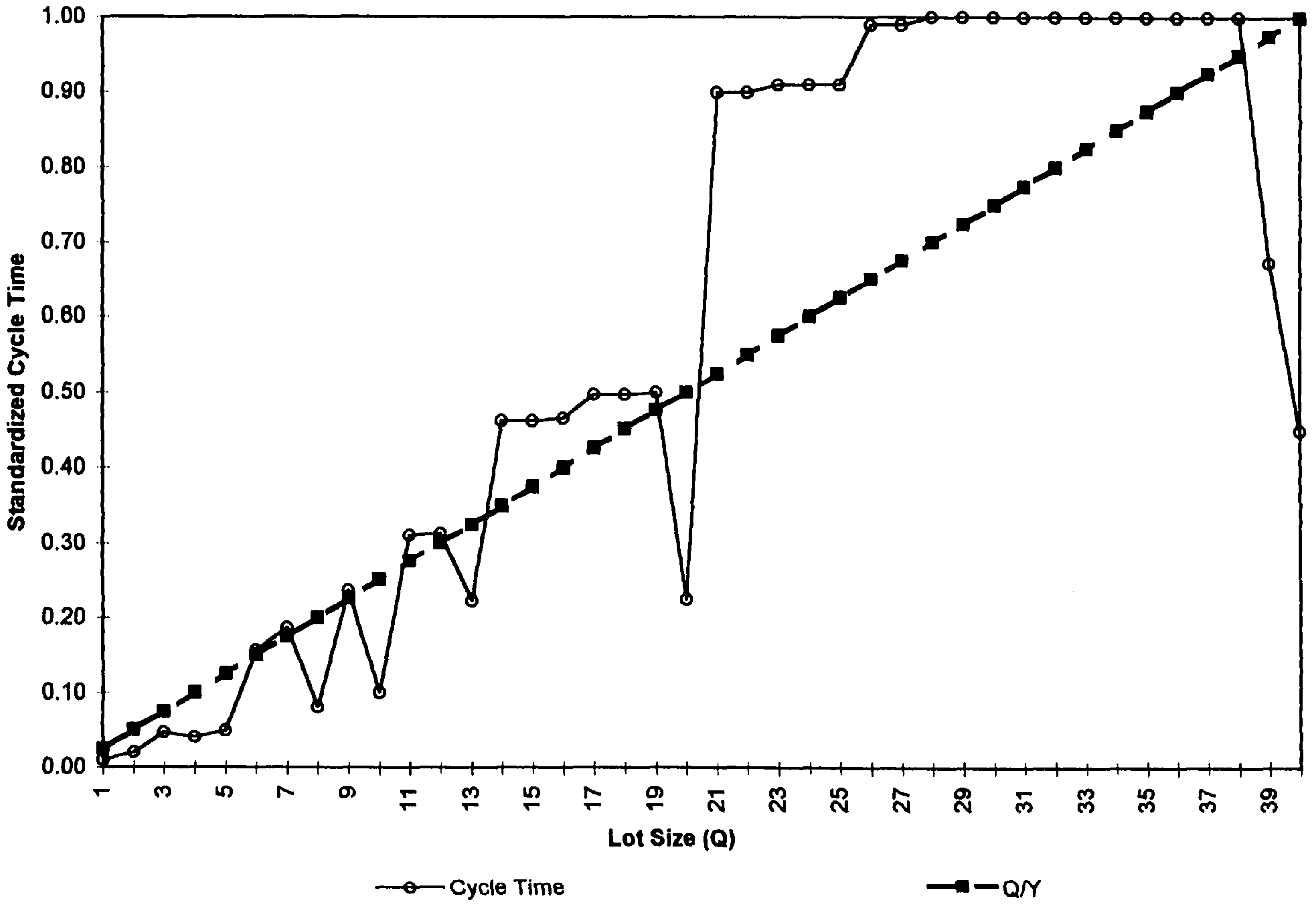


Figure 5-2: Expected Cycle Time versus Lot Size

Starting with Little's Law, where cycle time is equal to the quotient of inventory divided by system output, an analytical model for cycle time can be developed. From the literature discussed in Chapter 2, we know that lot size is strongly related to work-in-process inventory levels. From the discussion at load capacity, we know that the system output of a system is controlled by load capacity utilization of the bottlenecking resource. Our analytical model for cycle time can be developed by substituting the bottlenecking resource's load capacity for system output, and lot size for inventory in Little's Law. To investigate this analytical relationship between lot size and the bottlenecking resource's load capacity, the analytical cycle time model will be compared to the expected cycle times calculated in Table 5-2. This comparison is illustrated in Figure 5-2. As can be seen in Figure 5-2, the analytical model for cycle time, though not capturing the modal spikes of the expected cycle time, does follow the trend of the expected cycle time.

In order to reflect this change in either the market price or the demand level with respect to lot size, Eqn. 5-2 has been modified, using the analytical model for the expected cycle time of the product. The revenues for the j^{th} product can now be expressed as follows:

$$R_j = T_j M_j a e^{(\lambda_j - \bar{\lambda}_j)} \qquad \text{Eqn. 5-3}$$

where, $\lambda_j = \frac{Q_j}{\psi_{bj}}$ is the cycle time of the firm for the j^{th} product, $\bar{\lambda}_j$ is the industry average cycle time for the j^{th} product, a is the expected percentage increase in price or demand given immediate delivery of the product.

5.5. Production Costs

In the transformation process, there are usually many steps required. As the production units (wafers) are processed through each of the processing steps, value is added until the unit is fully transformed into the finished product. At each of these steps, costs are accumulated until, at the end, there is a total cost of production. Each processing step involves one or more resources and has a unique labor cost (L_{ij}), and a cost of consumables (C_{ij}) associated with it. The cost of consumables includes all raw materials (i.e., oils, acids, water, photoresist, etc.) and electricity consumed during the processing activity. The labor costs are computed as the labor rate times the direct man hours charged to that processing activity.

Traditionally, all production labor hours were directly chargeable to an operational process. With Goldratt's theory of constraints, a different perspective on the accounting of labor costs was presented (Goldratt, 1980; Goldratt and Fox, 1986; Goldratt and Cox, 1992). Goldratt showed that, during all processing activities, the operators will have periods of activity directly associated with the process and periods of slack time. In most firms, there is little data available on how much slack time operators really have. Thus, in order to simplify the accounting and decision-making process, labor costs are assigned to overhead. Where this data is available from industrial engineering time and motion studies, the direct labor costs should be accounted for in the production costs of the product and the slack time should be accounted for in the firm's overhead costs.

Operator activities that are directly related to the production process are those activities associated with the operating of equipment while it is running. Activities that should be included in the setup costs are discussed in section 5.6. All other activities, such as recording processing information (transactions), moving work-in-process inventory from one work station to another, and idle time should be accounted for in the firm's overhead. Figure 5-3 illustrates the relationships between the above mentioned variables and production costs.

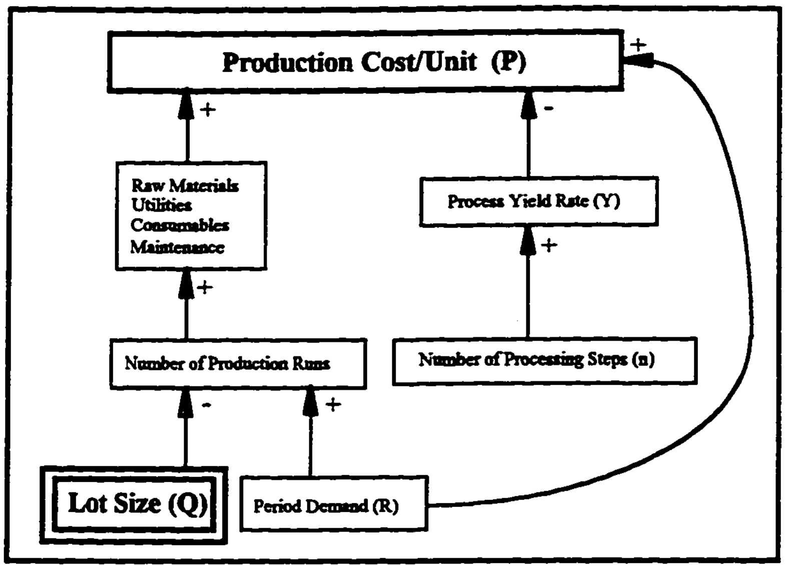


Figure 5-3: Relationship Diagram for Production Costs

In today's business environment, being able to trace lots through the production cycle has become increasingly more important due to liability risks and government regulations (Steele, 1995). Another, and probably more important, reason for lot traceability is the documentation of the process. Without this type of documentation, process improvement is virtually impossible (Enos, 1993). If lots are randomly subdivided at each step in order to maximize capacity utilization, it becomes impossible to trace what happened to each unit in the lot at the end of the transformation process. Trietsch and Baker (1993) also point out that by allowing variable lot sizes from machine to machine, complex paperwork may be required and thus, because of time and cost considerations, may be impractical.

Thus, lot integrity must be maintained throughout the production process. By this, it is meant that all production units in the lot will undergo the exact same processing, and if units from two separated lots are being processed simultaneously, all the units from both lots are processed at the same time, in the same load.

The following example illustrates the concept. Given a processing step having a capacity of twenty-five units, and a lot size of ten units, only two lots can be processed at a time. For this lot size, each processing run will be five units under capacity. In this situation, there is a temptation to break a lot into sublots of five units in order to fully utilize the capacity of the resource. However, this act will destroy the lot's referential integrity. Two different operations were applied to the subdivided lot and databases containing the referential histories of that lot's processing will not be able to specify both.

In this same example, if the lot size was reduced to eight units, three lots could be processed simultaneously, resulting in processing runs that were only one unit under capacity. From this example, it can be seen that, as lot sizes decrease (except at sizes that are an even multiple of the capacity), these under capacity production runs will have a larger impact on system output and on the production cost of each unit processed.

From the theory of constraints (Goldratt, 1980; Goldratt and Cox, 1992; Goldratt and Fox, 1986; Stien, 1994; Umble and Srikanth, 1990), we know that undercapacity process runs are generally not a problem except at the bottlenecking resource. Therefore, as a general rule, lots should be an even multiple of the bottlenecking resource's capacity, and probably should not exceed the capacity of any other resource in the transformation process. For production runs that are made at less than total capacity, the per unit cost of that run will be higher than the per unit cost of a full capacity run. By using lot sizes that fully utilize the bottlenecking resource's capacity, system output is maximized. Thus, proposition 1 can be supported.

The production cost per unit is computed as the cost of raw materials plus processing costs per unit. There are two categories of constraints on the production system that will affect the number of units that can be processed in a given time period: internal and external. When external demands are less than the production capacity of the firm, the constraint is referred to as an "external constraint." An "internal" constraint exists when the firm's production capacity is less than the market demand.

Assuming that all units started will complete the process defect free, the production cost for the j^{th} product is calculated as follows:

$$P_j = \sum_{i=1}^{n} T_j \left(m_j + \frac{C_{ij} + L_{ij}}{Q_j \eta_i} \right) \qquad \text{Eqn. 5-4}$$

where, m_j is the raw materials cost for the j^{th} product, C_{ij} is the cost of consumable for the j^{th} product at the i^{th} operation, L_{ij} is the labor cost for the j^{th} product at the i^{th} operation, $\eta_i = \text{Rounddown}\left(\frac{\psi_i}{Q_j}, 0 \right)$ = the number of lots of the j^{th} product that can be processed at the i^{th} machine per production run, and Q_j is the lot size of the j^{th} product. In reality, few processing activities are perfect. Because of statistical fluctuations (variance) in the process, there is usually some level of scrap generated. Scrap costs need to be considered in the total cost of production. Due to this production loss, resulting from defective items, in order to have the demanded amount of product at the end of the period, the number of production units started must be greater than the amount needed. The calculation for the number of production units started is:

$$\textbf{Production units started} \approx \sum_{j=1}^{k} \frac{T_j}{Y_j}, \qquad \text{Eqn. 5-5}$$

where Y_j is the process yield of the j^{th} product. Thus, by adjusting the production costs to include scrap costs, Eqn. 5-4 expands to:

$$P=\sum_{j=1}^{k}\frac{T_j}{Y_j}\left[\underbrace{\sum_{i=1}^{n}\left(Y_j m_j+Y_j\frac{C_{ij}+L_{ij}}{Q_j\eta_i}\right)}_{\text{defect free portion}}+\underbrace{\sum_{i=1}^{n}\left(\left(1-Y_j\right)m_j+\left(1-Y_j\right)\frac{C_{ij}+L_{ij}}{Q_j\eta_i}\right)}_{\text{defective (scrap) portion}}\right]. \qquad \text{Eqn. 5-6}$$

The production cost for the j^{th} product can now be expressed as follows:

$$P_j=\frac{T_j}{Y_j}\left(m_j+\sum_{i=1}^{n}\frac{C_{ij}+L_{ij}}{Q_j\eta_i}\right) \qquad \text{Eqn. 5-7}$$

where, $P=\sum_{j=1}^{k}P_j$.

When the constraint is an "internal constraint," opportunity costs are incurred as a result of scrap. According to the theory of constraints, nonbottleneck operations have greater system output capacity than the bottlenecking operation. Thus, with an external constraint, where the bottleneck is at the end of the process, there should be sufficient capacity to make up for scrapped units. In the case of the internal constraint, where the bottleneck is located within the process, only those operations preceding the bottleneck can make up for scrapped units. This limitation on the internally constrained system is because the capacity of operations following the bottleneck are limited to the system output of the bottleneck. In this case, the production units that are scrapped at or beyond the bottleneck will carry the additional opportunity cost of lost profits. Given n_j processing steps for the j^{th} product, with the bottleneck operation for the j^{th} product being located at the g^{th} processing step, the opportunity cost due to defective units is:

$$\text{Op. Cost of defect} = \frac{T_j}{Y_j}\left(1 - Y_j\right)\left(\frac{(n_j - g_j)}{n_j}\right)\xi_j \qquad \text{Eqn. 5-8}$$

where, ξ_j is the contribution to profits of the j^{th} product. The production cost for the j^{th} product is now expressed as:

$$P_j = \frac{T_j}{Y_j}\left[m_j + \sum_{i=1}^{n}\left(\frac{C_{ij} + L_{ij}}{Q_j \eta_i}\right) + \left(1 - Y_j\right)\left(\frac{\left(n_j - g_j\right)}{n_j}\right)\xi_j\right] \qquad \text{Eqn. 5-9}$$

With this expression for the calculating of production costs, proposition 2 can be supported.

5.6. Overhead costs

One of the major deficiencies of EOQ-based models is that they fail to consider such variables as work-in-process inventories (Corbey and Jansen, 1993) in the determination of overhead costs. Lead times can be reduced along with work-in-process inventory and safety stock with smaller lot sizes. Figure 5-4 shows the relationships that affect overhead costs.

According to generally accepted accounting principles, inventory carrying costs are absorbed in the overhead costs. EOQ-based models try to find an optimal inventory level through the minimization of overhead costs, and other, expected costs. With the increased focus on competitive imperatives such as speed and flexibility, it is generally agreed that firms should not hold inventory any longer than is required. Work performed by Corbey and Jansen (1993) found that lot size has a large influence on cycle times, work-in-process, and safety stock. Research performed by Guo (1994, p. 235) found that,

> changes in ending inventories are (1) negatively correlated with changes in net income, (2) positively correlated with changes in the inverse gross margin ratio, (3) positively correlated with changes in operating expenses, and (4) positively correlated with changes in other expenses.

The longer the actual cycle time, with respect to the ideal cycle time, the greater is the overhead cost factor (F). As work-in-process piles up around work centers, processing activities become increasingly more inefficient and work flow becomes increasingly more congested and sporadic (Chase and Aquilano, 1995). Given the current trend in manufacturing of balancing production capacity with demand, as the production rate nears demand, the denominator of the EPQ expression (reference Eqn. 2-4) approaches zero. This causes the lot size calculation for EPQ to approach infinity. This is the opposite of the understanding of overhead costs accrual that can be derived from current literature, as well as, this concept does not recognize the effects of cycle time. Thus, it does not allow for the reduction of overhead costs due to improvements in cycle time. By incorporating cycle time into the overhead costs function, cost improvements due to cycle time reduction can be accounted for.

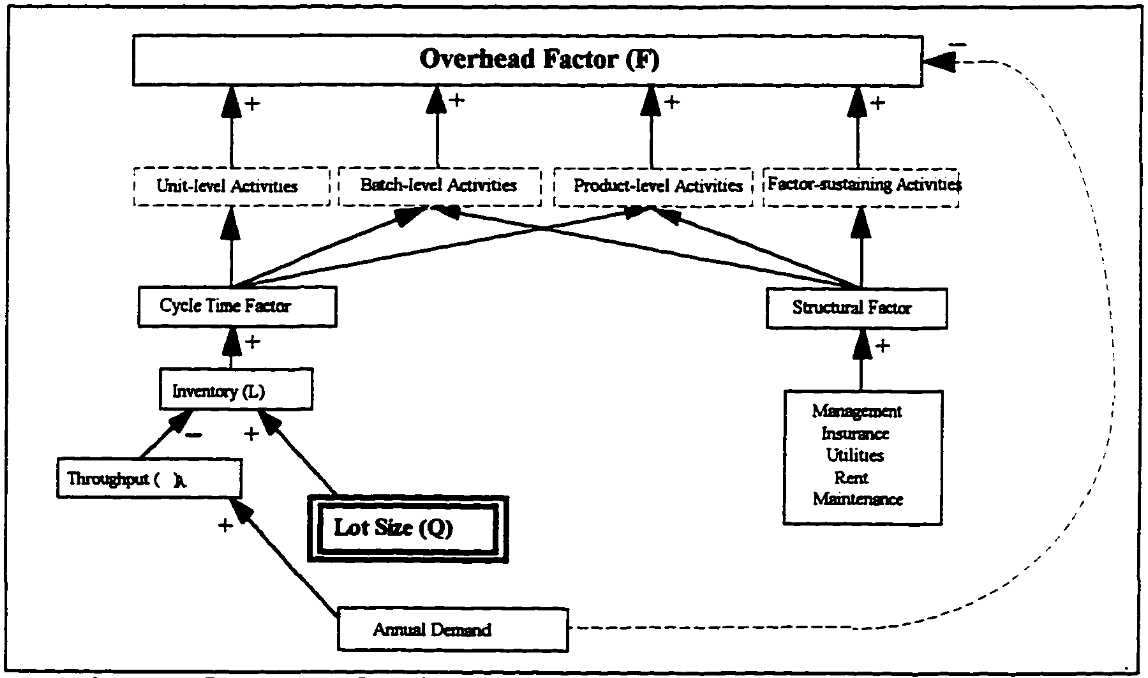


Figure 5-4: Relationship Diagram for Overhead Costs

Synchronous manufacturing techniques have shown us that the difference between actual cycle time and ideal cycle time is strongly related to lot size (Goldratt, 1980; Goldratt and Fox, 1986; Goldratt and Cox, 1992; Umble and Srikanth, 1990). As actual cycle time gets larger with respect to the ideal cycle time, inventory will increase. Enos (1993) points out that any source of inventory will add costs, not value. These costs include handling, expediting, storage, counting, tracking, damage, and obsolescence (Chase and Aquilano, 1995; Enos, 1993) The current method of assessing the firm's overhead costs can be modeled as follows,

$$\mathrm{H} = \sum_{j=1}^{k} \mathrm{F}_j \sum_{i=1}^{n} \gamma_{ij} \overline{\eta}_{ij} Q_j \qquad \text{Eqn. 5-10}$$

where, F is the overhead factor of the jth product, γ_i is the unit value added at the ith processing step for the jth product, $\overline{\eta}_{i,}$ is the average number of lots at the ith processing step for the jth product, n is the number of steps in the production process, and k is the number of product models produced. Thus, the expression $\sum_{i=1}^{n} \gamma_{ij} \overline{\eta}_{ij} Q_j$ is equivalent to the total production cost of the jth product.

Overhead costs are believed to be compressed of two parts; a variable component and a fixed component. The fixed component would include the costs of facility sustaining activities and the non-lot size sensitive costs of the batch-level and the product-level activities. The variable component of overhead costs would be composed of expenses that are incurred due to the costs of unit-level activities, and the lot size sensitive costs of batch-level and product-level activities.

By definition, the capacity of the bottlenecking resource limits the production system's maximum system output. It has also been established in current literature that lot size is strongly related to the firm's inventory level (Corbey and Jansen, 1993; Enos, 1993). As previously stated, as inventory levels increase beyond a reasonable level, there is a corresponding decrease in production activities. This decrease in production activities will result in a decrease in operating expenses. Thus, these variable expenses can be modeled using a cycle time variable. To account for these decreasing expenses the inventory relationship needs to be modified with a scalar (β). By modifying the analytical model for cycle time developed in section 5.4, the following expression can be utilized to model the cycle time relationship,

$$\text{Cycle time (W)} = \sum_{j=1}^{k}\left(\frac{Q_j}{\psi_j}\right)\beta_j \qquad \text{Eqn. 5-11}$$

where, β_j is a scaling constant for the j^th^ product.

The fixed component in overhead costs is primarily related to those activities associated with supporting a facility's general manufacturing process. The cost components captured by this variable are relatively insensitive to changes in production policies and can be expressed as follows,

$$K = \sum_{j=1}^{k} \theta_j \qquad \text{Eqn. 5-12}$$

where, θ_j is the fixed portion of the overhead costs allocated to the jth product. Thus, the new overhead cost factor is the sum of the fixed and variable components and can be expressed as,

$$F' = W + K = \sum_{j=1}^{k} \left(\frac{Q_j}{\psi_j}\right)\beta_j + \theta_j \, . \qquad \text{Eqn. 5-13}$$

Given a total production cost per unit of P, the expression for the firm's overhead costs per production unit is,

$$H_j = P_j F_j = P_j\left(\left(\frac{Q_j}{\psi_j}\right)\beta_j + \theta_j\right) . \qquad \text{Eqn. 5-14}$$

From this expression, proposition 4 can be supported.

5.7. Setup Costs

Setup costs are those costs associated with: (1) the removal of processed materials from the machine, (2) the cleaning of machinery after processing but prior to the next setup, (3) the placing of unprocessed materials into the machine, and (4) the setting of machine parameters for the next processing run. As seen in Figure 5-5, lot size has an inverse relationship to the setup cost per units.

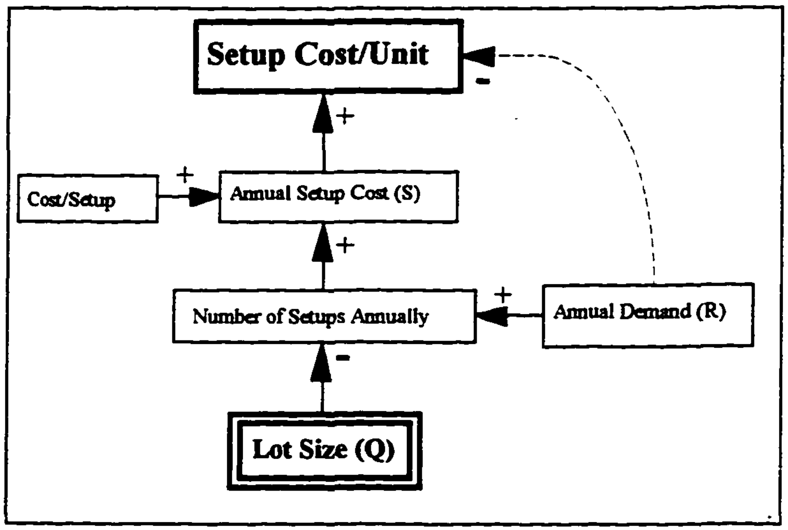


Figure 5-5: Relationship Diagram for Setup Costs

Given a demand level of D_j for the j^{th} product, the expected number of total setups for a given demand period is:

$$s_j = \sum_{i=1}^{n} \frac{D_j E_i}{\eta_i Q_j} \qquad \text{Eqn. 5-15}$$

where, E_i is the number of reentrance flows that the j^{th} product makes into the i^{th} processing operation.

Setups involve the loading and unloading of production units, cleaning of the processing equipment as required, changes in consumable materials, and the loading of processing recipes. The conventional method for determining setup costs is specified as:

$$S = \sum_{j=1}^{k} \sum_{i=1}^{n} \left(\tau_{s_{ij}} L_i + C_{ij} \right) s_i \qquad \text{Eqn. 5-19}$$

where, $\tau_{s_{ij}}$ is the time required to setup the i^{th} processing step for the j^{th} product in man hours, L_i is the labor rate of the i^{th} processing step, C_{ij} is the cost of consumable for processing the j^{th} product at the i^{th} processing step, and s_i is the expected number of setups at the i^{th} processing step calculated using Eqn. 5-26.

In determining these setup costs, Raturi (1989) said that there were two major problems:

1. Cost accounting methods determine setup costs based upon the allocation of overhead and direct labor costs. In making operational decisions, these types of costs are considered sunk costs.
2. Economically, additional setups are dependent upon the resource capacity. If there is excess capacity, the cost is minimal. If the resource is a bottleneck or a capacity constrained resource, the cost is very high.

Raturi's view point is consistent with the theory of constraints and the principles of synchronous manufacturing. The true impact of setups is felt through the amount of lost system output due to the time spent setting up the bottlenecking resource (Goldratt, 1980; Goldratt and Fox, 1986; Goldratt and Cox, 1992; Stien, 1994; Umble and Srikanth, 1990). In addition, Edstrom, Anders, and Olhager (1987) have demonstrated that as setup times and costs are reduced, economic order quantities can be economically reduced.

If the view point that both the machine costs and the labor costs should be considered as overhead is taken, and as such are accounted for in the firm's overhead costs. The true cost of setups then is the resulting lost of system output and the cost of any consumable utilized in the setup process. In order to develop this construct in a general application format so that both view points can be utilized, the direct labor costs for the setup activities are considered along with consumables. The remaining question is how to determine this lost of system output. The maximum system output of a production system is determined at the bottleneck. Given setup time is zero, then the output of a system is:

$$T = \sum_{j=1}^{k} \frac{\Psi_{bj}}{\tau p_{bj}} Nh \qquad \text{Eqn. 5-20}$$

where, N is the number of operating days in the time period, h is the number of operating hours in a day, and τ_{pbi} is the processing time of the bottleneck for the j^{th} product in hours. Furthermore, given that the total number of setups can be expressed by Eqn 5-26. Then the total amount of setup time at the bottleneck can be expressed as:

$$\text{Setup time at the bottleneck} = s_i \tau_{s_{bj}} \qquad \text{Eqn. 5-21}$$

where, τ_{sbj} is the setup time of the bottleneck for the j^{th} product in hours. The total cost of setups can now be expressed as:

$$S = \sum_{j=1}^{k} \sum_{i=1}^{n} c\xi_j \left(\frac{R_j E_j}{\eta_{bj} Q_j} \right) \left[\frac{\tau_{sbj}}{\tau_{pbj}} + C_{ij} + L_{ij} \right] \qquad \text{Eqn. 5-22}$$

where, ξ is the per unit contribution to net profits, τ_{sbj} is the total amount of time spend performing setups at the bottlenecking operation of the j^{th} product, τ_{pbj} is the average amount processing time of the j^{th} product at its bottlenecking operation, and τ_{sb}/τ_{pb} is the total number of additional product runs that could of been made if there had been no setup time required.

Another critical item in the determination of setup costs is the determination of the time required to setup each processing step. One method of accounting for the overall average time of setting up each process step is to utilize the basic learning curve techniques that are of standard usage in industrial engineering. Buffa (1984, p. 34) explains that,

> It is well known in manufacturing that as experience is gained through production, unit

> costs are usually reduced. It was originally thought that cost improvement was simply the result of a learning effect by workers reflecting the development of skill and dexterity when a task is performed repetitively. Now, however, this effect is recognized as resulting from a wide variety of additional sources, such as improvements in production methods and tools, improvement product design, standardization, improved material utilization, reduction of system inventories, improved layout and flow, economies of scale, and improvements in organization. The entire effect might be called organizational learning. Actually, the worker learning effect occurs rather quickly and is minor compared to the total learning effect.

The learning curve concept is expressed as:

$$\tau_n = \tau_1 n^{\left(\ln(r)/\ln(2)\right)} \qquad \text{Eqn. 5-23}$$

where, τ_n is the average number of hours per unit when n units are produced, t_1 is the hours required to setup the first unit, and r is the learning rate.

Replogle (1988) applied the learning curve concept to the EOQ setups to emphasize the strategic value of lot sizing. By applying this concept the setup time of the bottleneck, setup time can be expressed as:

$$\tau s_{bj} = \tau_{b1}\left(\frac{R_j}{\eta_{bj}Q_j}\right)^{\left(\ln(r)/\ln(2)\right)} . \qquad \text{Eqn. 5-24}$$

By making this substitution, the total cost of setups for the jth product is:

$$S_j = \sum_{i=1}^{n} \xi_j \left(\frac{D_j E_j}{\eta_{bj} Q_j} \right) \left[\frac{\tau_{sbj}}{\tau_{pbj}} \tau_{sb1} \left(\frac{D_j E_j}{\eta_{bj} Q_j} \right)^{\left(\ln(r) / \ln(2) \right)} + C_{ij} + L_{ij} \right] . \qquad \text{Eqn. 5-25}$$

5.8. Proposed New Model

The objective of our new focus is to maximize the firm's net profits. This is accomplished by increasing system output while simultaneously decreasing operating expenses. From the above propositions, we contend that optimally sized production lots can increasing system output while simultaneously decreasing operating expenses.

Goldratt (1990) has defined several terms that describe the measurement of the production process as follows:

- Throughput is defined as "the rate at which the system generates money through sales" Goldratt (1990, p. 19). System output is measured as gross revenues less raw materials cost. Due to the probability of scrap in the process, and to ensure that all raw materials are accounted for, the deduction for raw materials is made in the production cost construct.
- Operating expense is defined as "all the money the system spends in turning inventory into system output" Goldratt (1990, p. 29).

- Net profits are defined as simply throughput minus operating expense" Goldratt (1990, p. 32). This relationship can be expressed in the following form:

$$NP = \Sigma_p T_p - \Sigma_c OE_c \ . \qquad \text{Eqn. 5-26}$$

As can be seen from the subscripts in Eqn. 5-26, throughput and operating expense are not in the same units. This is due to how traditional cost accounting methods have accounted for and defined overhead costs. This problem is corrected by redefining overhead costs, or overhead, from being all the indirect expense irrespective of product, to assessing indirect expense by product and calling it burden. Goldratt (1990) also points out that inventory has a very significant impact on net profits through operating expense as carrying costs. Thus, indirect overhead expenses are expressed as a function product, and net profits are expressed as:

$$NP = \Sigma_p T_p - \Sigma_p OE_p \ . \qquad \text{Eqn. 5-27}$$

By breaking operating expense into the three basic categories of production costs, overhead costs, and setup costs, and using gross revenues (MR) in place of system output, net profits can be modeled as:

$$NP = \Sigma_p MR_p - (\Sigma_c P_c + \Sigma_c H_c + \Sigma_c S_c) \ . \qquad \text{Eqn. 5-28}$$

Thus, subject to the constraints placed upon the preceding constructs, the model for calculating annual net profit is denoted as:

$$\text{Max}\{\text{NP}\} = \text{Max}\left\{\sum_{j=1}^{k}\left(R_j - P_j - H_j - S_j\right)\right\} \qquad \text{Eqn. 5-29}$$

where,

$$\mathrm{R_j} = \mathrm{T_j M_j} a e^{\left(\lambda_j - \bar{\lambda}_j\right)}, \quad \text{where } \lambda_\mathrm{j} = \frac{Q_j}{\Psi_j} \qquad \text{Eqn. 5-3}$$

$$\mathrm{T_j} = Y_j D_j\left(\frac{\eta_{bj} Q_j}{\Psi_{bj}}\right) \quad \text{s.t. } \mathrm{T_j} \le \text{max system output}$$

$$\text{if } D_j << \text{max system output, then } D_j\left(\frac{\eta_{bj} Q_j}{\Psi_{bj}}\right) \cong D_j \qquad \text{Eqn. 5-1}$$

$$P_j = \frac{T_j}{Y_j}\left[m_j + \sum_{i=1}^{n}\left(\frac{C_{ij} + L_{ij}}{Q_j \eta_i}\right) + \left(1 - Y_j\right)\left(\frac{\left(n_j - g_j\right)}{n_j}\right)\xi_j\right] \qquad \text{Eqn. 5-9}$$

$$H_j = P_j\left(\left(\frac{Q_j}{\psi_j}\right)\beta_j + \theta_j\right) \qquad \text{Eqn 5-14}$$

$$S_j = \sum_{i=1}^{n} \xi_j\left(\frac{D_j E_j}{\eta_{bj} Q_j}\right)\left[\frac{\tau_{sbj}}{\tau_{pbj}} \tau_{sb1}\left(\frac{D_j E_j}{\eta_{bj} Q_j}\right)^{\left(\ln(r)/\ln(2)\right)} + C_{ij} + L_{ij}\right]. \qquad \text{Eqn. 5-25}$$

In the above analytical constructs, Y_j has been described as the process quality of the jth product. Due to the lack of data on how Y_j reacts as a function of either lot size or cycle time, in this research it is used as a constant with respect to the jth product. Where data is available, the practitioner should make every effort to model the j^{th} product's yield rate as a function of either lot size or cycle time. The reason for this is that the more time sensitive the yield of a product is, the greater the cost of poor quality with respect to cycle time.

5.9. Summary

In accordance with the research methodology presented in Chapter 4, a problem was identified, observations made, and a problem statement developed and presented in Chapter 1. Chapters 2 and 3 provided a background of the problem. Based upon the current literature, reviewed in Chapter 2, and upon theory, a framework was developed in the form of a net profit maximizing lot sizing model (reference Eqn. 5-29). This model is consistent with the theory of constraints, while remaining flexible enough for the usage of various cost accounting methods. There are four major analytical constructs that make up this model: a revenue generation model, production cost model, overhead cost model, and a setup cost model. Chapter 6 shall describe the experiment designed to test the model presented, and Chapter 7 shall develop the hypotheses testing the model, as well as the results of these tests.

CHAPTER 6

THE PRODUCTION DATA AND THE COMPUTER SIMULATION MODEL

In Chapter 5, four analytic constructs were developed to explain the various relationships found in the production process, and a net profit maximization model was developed. In support of the validation process to be described in Chapter 7, production data from the integrated circuit fabrication process at the Texas Instruments, Inc., plant in Lubbock, TX, were collected, and a computer simulation model was built. The production data collected will be described in the first section of this chapter. A computer simulation model is derived from this data. This simulation model will be discussed in the second section of this chapter.

6.1. The Production Data

The data collection initiative described in this chapter performs a support role in the context of this dissertation. It is not the primary method or vehicle of knowledge discovery because of the traditional analytic, deductive nature of lot size modeling. The data that were collected shall be described below. Because data were being collected from only one company, there is some concern about the generalizability of any finding from the data. The data was collected from the Texas Instruments, Inc.'s Lubbock Plant, CMOS group.

With respect to the concern about the generalizability of the result of this investigation, the Texas Instruments, Inc.'s Lubbock Plant is fairly typical of most existing types of wafer fabs. It is designed about a product type layout, where similar types of equipment are group together. This plant is also considered one the best, and most productive plants owned by Texas Instruments. Because of these reasons, the results of this research are expected to be generalizability across the semiconductor industry.

6.1.1. Description of the Data

In Chapter 3, the basic process for the fabrication of an integrated circuit was described. In every production process, there are parameters and costs associated with the operation of the process. These parameters define how the work will be processed. The costs define the financial impact of that work. The data collected in this research include the operational parameters of the production process at the Texas Instruments, Inc.'s Lubbock plant, and the cost accounting data associated with this process. The costing data were collected by quarters for over a five-year period starting with the first quarter of 1992 and ending in the fourth quarter of 1996.

The Process Parameters. The typical environment for the fabrication of integrated circuits is the job shop. Due to the reentrant flows throughout the processing cycle, a process layout is utilized. In the process layout, machines of similar function are located in the same work centers. Operational parameters that were factored into the simulation model include: the average percentage of utilization, the average percentage of machine availability, process recipes, processing times, and the average length of time for a setup of the same or compatible process recipe on the same machine. Also, the average time for a setup of a different, incompatible process recipe on the same machine, the process compatibility code, and the machine's load capacity. Because of the proprietary nature of these expenses, Texas Instruments has requested that these data not be published. Their request will be honored.

6.1.1.1. The Processing Costs. The products produced in the Texas Instruments, Inc.'s Lubbock plant are very similar in nature. The value added per production unit is not significantly different from one product type to the next. Because of this, the direct costs of production (i.e., consumable materials, electricity, and repair and maintenance expenses) have been allocated as dollars per hour of machine run time instead of by product type. Furthermore, due to the cost data not being allocated down to the model (device type) level, a direct comparison between the production data and the simulation's costs, or between the production data and the analytical model's costs, will not be possible. A regression analysis will be conducted on the production data to identify significant operational variables that can be utilized for prediction of costs for the simulation.

As mentioned in section 6.1.1, actual operating expenses for the Texas Instruments, Inc.'s Lubbock plant, C-MOS group were collected from the first quarter of 1992 through the last quarter of 1996. These expenses have been separated into seventeen different categories: materials, inventory deltas, cost adjustments, direct labor, indirect labor, benefits, supplies, repair and maintenance, sundries, depreciation, lease, taxes, occupancy, utilities, computer paper, other services, and other income and expenses. These operating expenses represent the total expenses of each quarter. Again, because of the proprietary nature of these expenses, Texas Instruments has requested that these data not be published.

An analysis shall be conducted on these data to ascertain if there are any differences in the costs associated with the 48-wafer lot size and the 24-wafer lot size. A full description of this analysis is in Chapter 7. If there is a difference between the derived costs of the simulation and any of the analytical models, a regression analysis shall be conducted to investigate which independent operational variables can be utilized to improve the prediction capability of the model in question.

6.1.1.2. The Products. The Texas Instruments, Inc.'s Lubbock plant produces numerous different products over the course of the year. Many of these products are produced simultaneously. Each product produced has its own unique process routing through the shop. Each product also may require slightly different processing requirements at any given machine, such as time and materials. From the products produced at the Lubbock plant, three have been selected for investigation. The selection criteria were based upon finding three products that differed significantly in their processing requirements and routing to create three separate bottlenecks within the production process.

6.2. The Computer Simulation

A simulation model was built to validate the constructs developed in Chapter 5. As the primary vehicle of validation, the simulation model will investigate the following questions:

1. What is the expected number of production runs at each operation in the transformation process for each lot size investigated?
2. What is the expected number of major and minor setups at each operation in the transformation process for each lot size investigated?
3. What is the expected throughput for the total system for each lot size investigated?
4. What is the expected work-in-process inventory level at each operation in the transformation process for each lot size investigated?
5. What is the expected cycle time of each product, and for the total system, for each lot size investigated?
6. What is the effect on operating expenses as expressed through production cost, overhead cost, and setup cost as the lot size varies?

6.2.1. Description of Parameters

As mentioned in Section 6.1.1.1, the typical environment for the fabrication of integrated circuits is the job shop. Due to the reentrant flows throughout the processing cycle, a process layout is typically utilized. It is also normal to find different machines of similar function in the same work centers. In order to simplify the simulation model for this research, it will be assumed that all machines in a work center are identical and are capable of processing all process recipes applicable to that work center. As shown in Figure 6-1, there are 60 work centers to be modeled for the production processes of interest.

Based upon the operational routing requirements of each device type, the simulation engine will make lot movements and work assignments. By referencing the product specific operational sequencing tables, the row pointer for a given operation can be found. These row pointers indicate in which row of the process specification table the work center and processing information can be found. With this information the simulation model routes lots to work centers and resources within the work centers.

6.2.2. Model Description

The Slam II simulation software was utilized in the development of the simulation model for this research. Figure 6-2 illustrates the basic logic flow of the Slam II simulation being used in this study. Because the FORTRAN side of SLAM II provides for greater speed and flexibility in modeling processes, the decision was made to use the FORTRAN interface, rather than the network interface, which is easier but slower and less robust.

Each lot of material to be released into the production system was defined using the following 15 attributes: (1) job start time, (2) due date, (3) current work center, (4) current processing code, (5) current operation number, (6) cumulative process yield, (7) cumulative production costs, (8) cumulative setup time, and (9) device type. Other job attributes that were used are; (10) current row pointer, (11) current machine number, (12) current operator number, (13) logout terminal number, (14) current batch array job pointer, and (15) previous batch array jobs pointer.

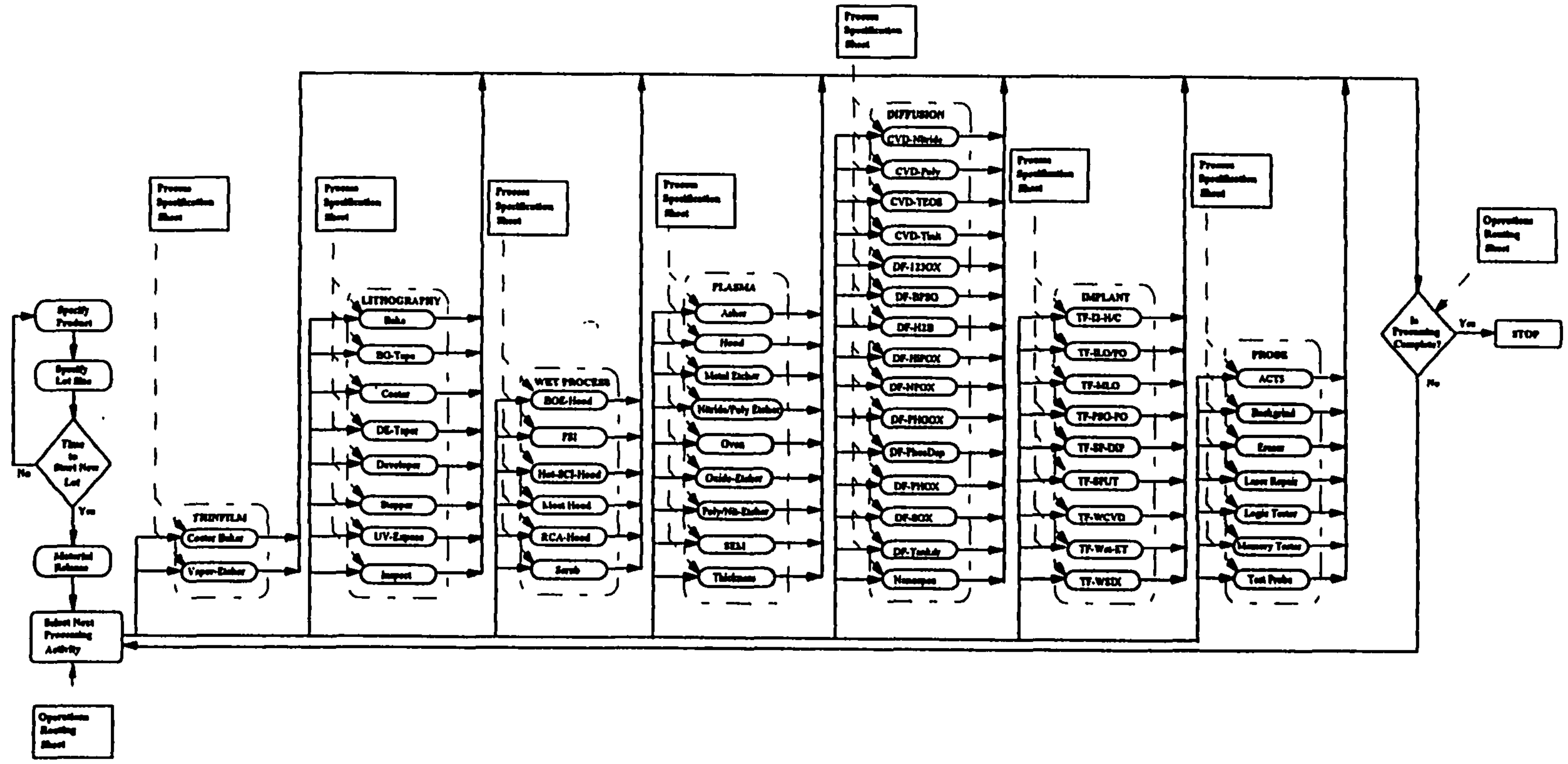


Figure 6-1: The Simulated Integrated Circuit Fabrication Process Flow

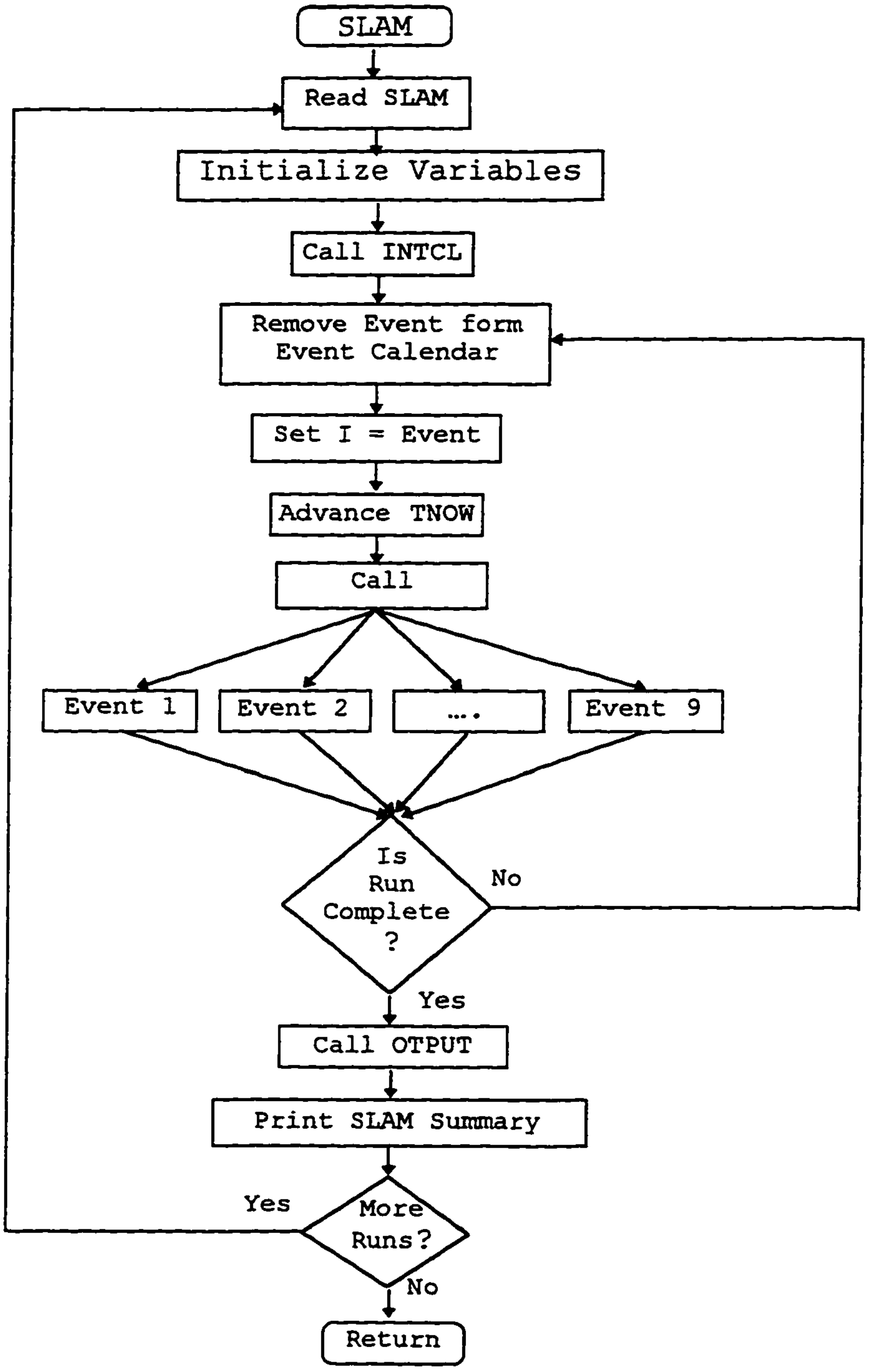


Figure 6-2: SLAM II Next Event Logic for Simulating Discrete Event Models
Source: Pritsker (1995)

6.2.2.1. Generic Material Flows. Figure 6-3 provides a generic material flow diagram for the work centers within the wafer fab. Figure 6-3 also shows when the operator and the machine resources would be busy during this material flow. Each of the boxes in Figure 6-3 coincides with one of the user written subroutines that will be described later.

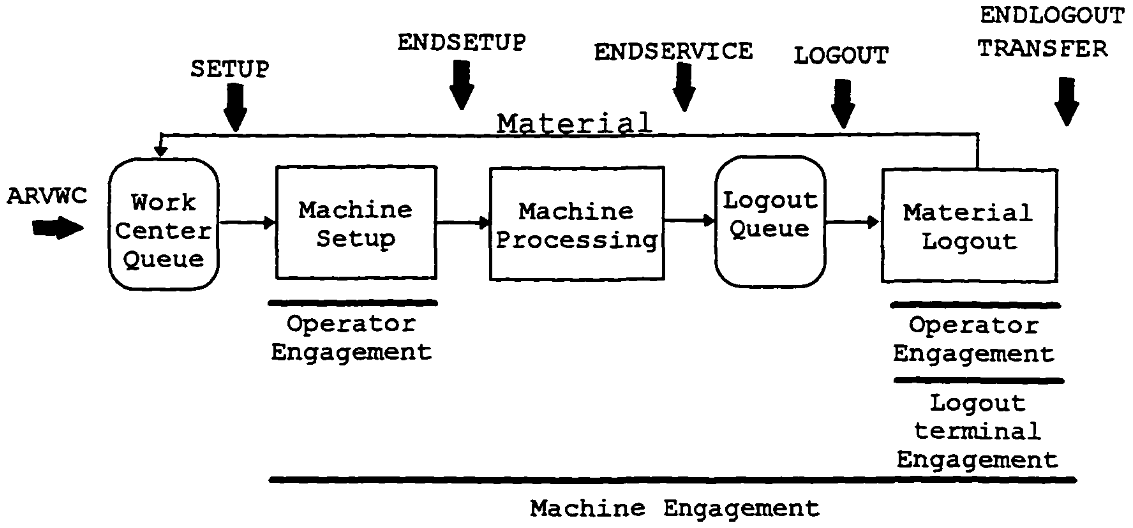


Figure 6-3: Work Center Material Flow and Resource Engagement

Material will enter the work center queue as a result of a raw material release into the shop, or because of a transfer routing from another work center. As a machine resource is freed up (set to idle), the operator will go to the work center queue and remove a job based upon the first-come, first-served queue priority system. If the machine's load capacity is greater than the lot size of the job selected, more jobs will be selected, if they are compatible with the first job's processing requirements.

During the setup operation, the wafers that comprise the jobs that were selected will be loaded into the machine, and the processing recipe will be electronically downloaded. Once the processing has started, the operator is free to perform other tasks about the work center. When processing is complete, the wafers will remain inside the machine until an operator is available to remove them. The logout queue is used to generate the random timing of the operator response to an end-of-service condition.

After the job(s) is unloaded from the machine, it is logged out of the work center via a mini-terminal located at each machine. When the logout activity is completed, if more processing requirements remain, the job(s) is transferred to the next work center and placed in queue. If all processing requirements have been completed, the job is removed from the shop. It is at this point that the simulation stops. In reality, the completed wafers are cut into the individual integrated circuits (chips) and packaged.

6.2.2.2. User-Written Subroutines. A main program and a series of user-written subroutines were utilized in this simulation model due to the discrete event nature of the model. The main program was used to define the arrays needed for the simulation, to read data into the defined arrays, and to initiate the Slam II system. Figure 6-4 provides the logic flow for the main program.

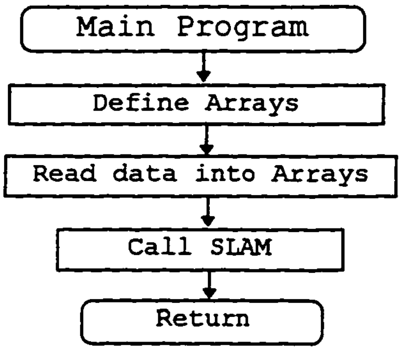


Figure 6-4: Main Program Logic

The EVENT subroutine is used to call the other subroutines as they are needed. Figure 6-5 illustrates the logic flow of this subroutine.

The INTLC subroutine is used to initialize the starting values for all the user-defined variables in the model. Figure 6-6 shows the logic flow of the INTLC subroutine.

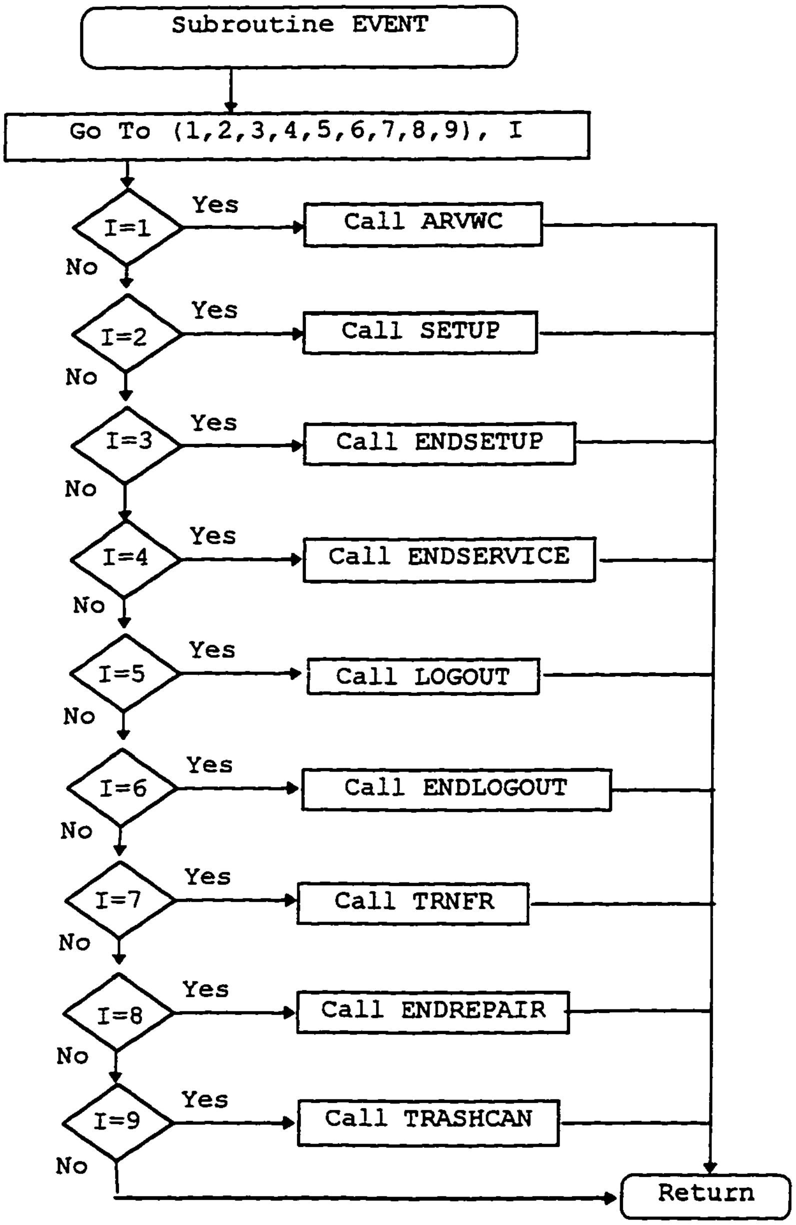


Figure 6-5: Subroutine EVENT Logic

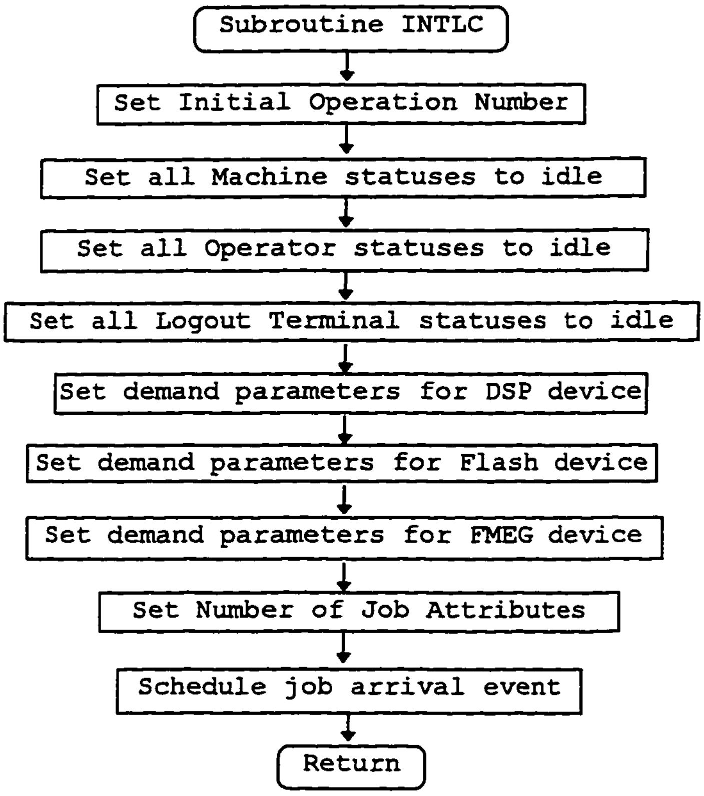


Figure 6-6: Subroutine INTLC Logic

The ARVWC subroutine releases new material into the production system being modeled. In this subroutine, a normal distribution is used to define the daily demand for each of the three product types being used. The Texas Instrument's Lubbock plant operates two twelve-hour shifts, seven days a week. New materials are released only at the beginning of each shift. Figure 6-7 shows the logic flow for the ARVWC subroutine.

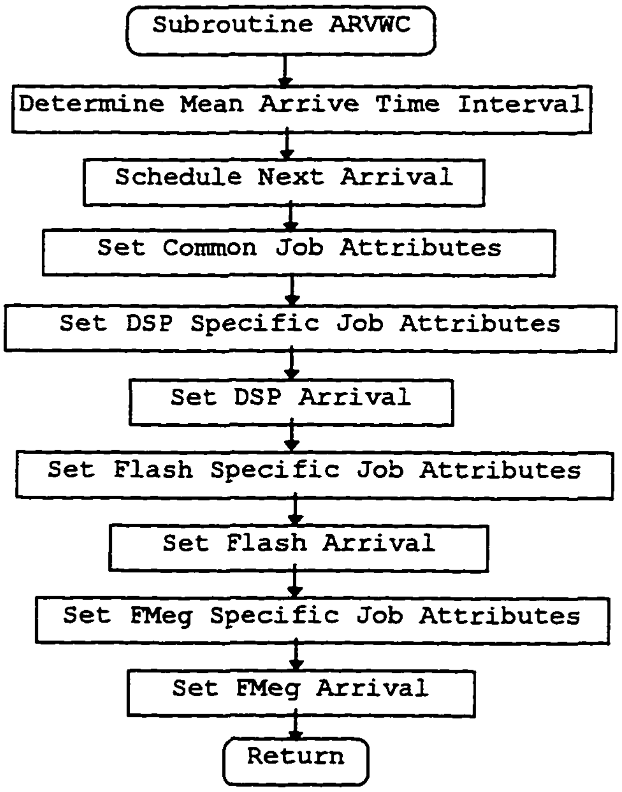


Figure 6-7: Subroutine ARVWC Logic

In Subroutine SETUP, the processing resources of the work center are checked to find both an idle operator and an idle machine. When both idle resources are found, they are assigned to the current job. If the machine in question is determined to be down for maintenance, the search for an idle machine continues. The maintenance check is based upon machine availability and mean-time-to-repair (MTTR) statistics that were provided by Texas Instruments. A random number is generated, and if the random number is greater than the machine availability statistic, then the machine is determined to be down for maintenance. The service time that the down machine is scheduled for is determined using a normal distribution with a mean equal to the MTTR, and a standard deviation of 25 percent of the MTTR. If SETUP fails to find both an available operator and an available machine, then the job is filed back into the work center's processing queue.

Once an operator and a machine have been found, the lot size of the job is compared against the machine's load capacity. If more load capacity exists than is required by the current job, the queue is searched for other compatible jobs that have a lot size less than or equal to the remaining load capacity of the machine. The criteria for selection is based upon similar processing requirements, and the search of the queue is based upon the first-come, first-served priority system. Once it has been determined that there are either no more compatible jobs in the queue or no more load capacity, the selected jobs are batched and setup servicing is scheduled.

The setup time utilized for scheduling is based upon whether the machine is currently setup for that processing requirement. If the machine is currently setup for the processing requirements of the batched jobs, then a regular setup is selected from the process specification table. If the machine was previously setup for a different process, then a conditional setup is selected from the table. The processing time for the required processing is retrieved from the table and stored in the batched job's attributes array. Figure 6-8 provides the logic flow for this event.

The end-of-setup (i.e., ENDSETUP) subroutine is used to initiate the next activity in the sequence, service. It does this by scheduling the end-of-service (processing) event. If there are any jobs in the work center's logout queue, the first job will be removed and scheduled for the LOGOUT activity. Figure 6-9 provides the logic flow for the ENDSETUP event.

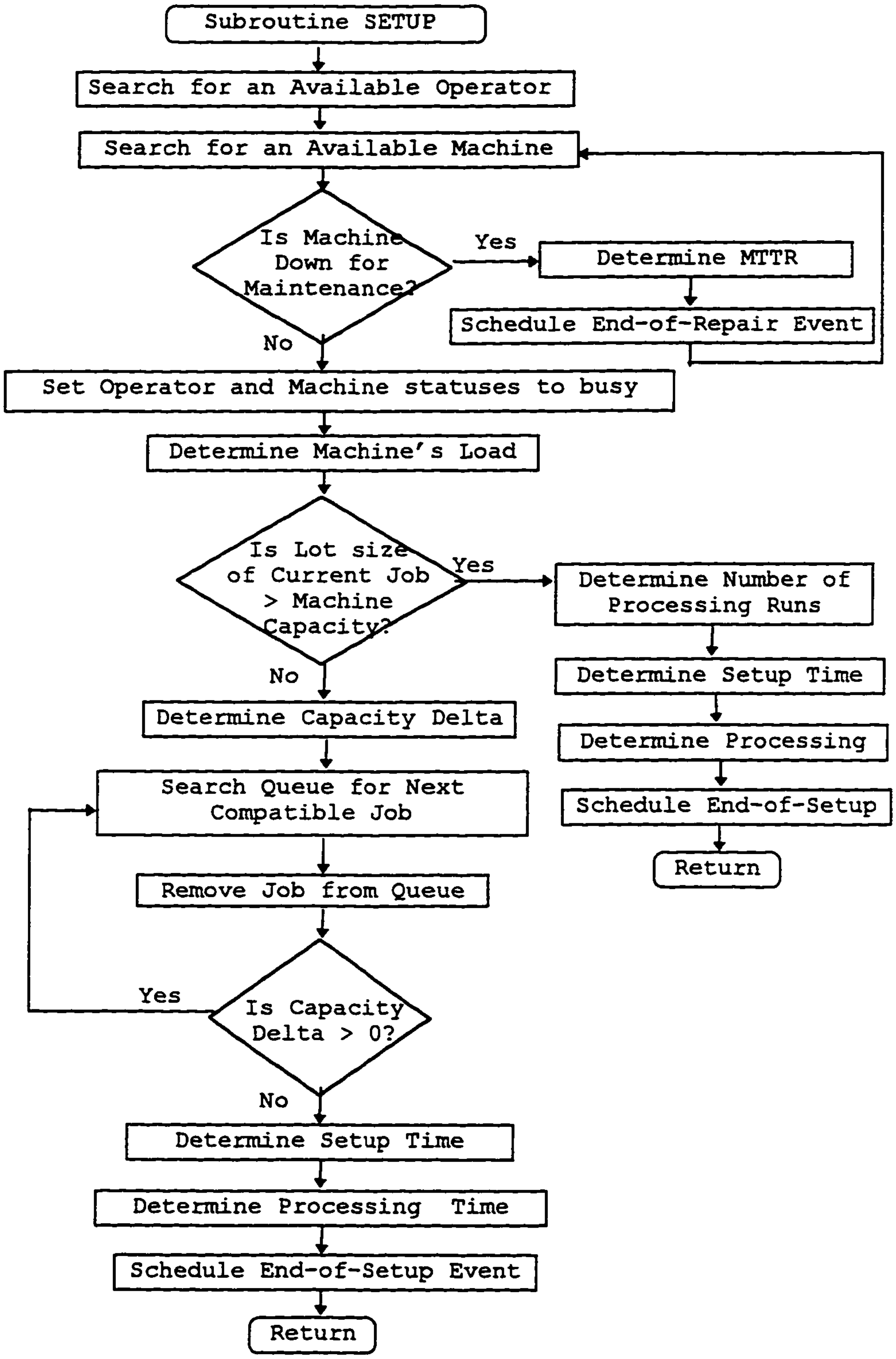


Figure 6-8: Subroutine SETUP Logic

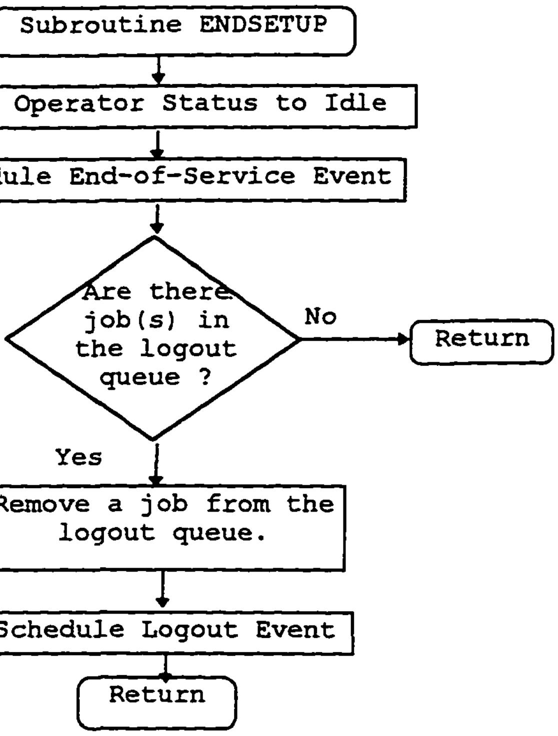


Figure 6-9: Subroutine ENDSETUP Logic

When the processing of a batched set of jobs is completed, the end-of-service event subroutine (ENDSERVICE) gets called. In this subroutine, the logout event is scheduled and the work center's processing queue is checked for more jobs. If there are jobs in the work center processing queue, the first job is removed and scheduled for SETUP. Queue priority is based upon the first-come, first-serviced rule. Figure 6-10 shows the logic for the end-of-service subroutine.

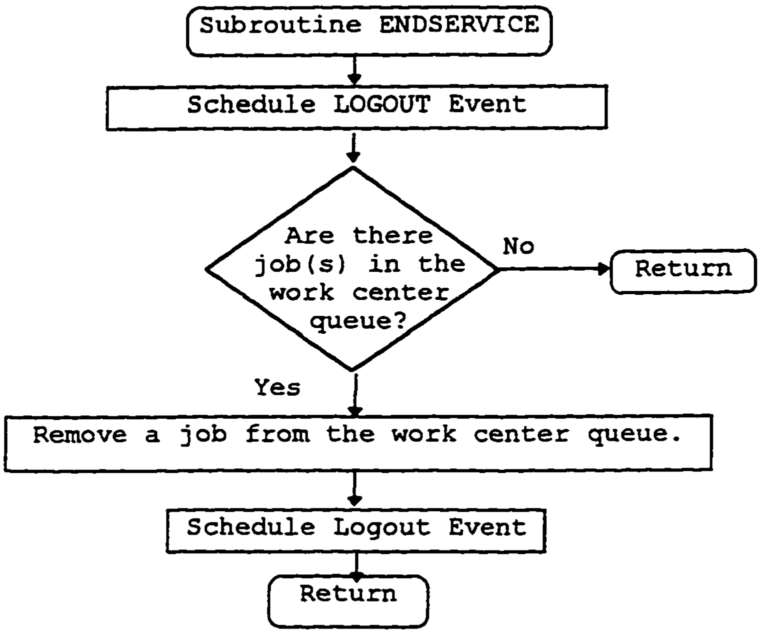


Figure 6-10: Subroutine ENDSERVICE Logic

The LOGOUT subroutine is used for the documenting of processing activities to the job log for each completed job. First, an idle operator is located, then the job is scheduled for the end-of-logout event. Figure 6-11 shows the logic flow for this subroutine.

The end-of-logout (i.e., ENDLOGOUT) subroutine denotes that all processing and documentation of the job has been completed. At this point, the jobs that were batched in the setup subroutine are unbatched, the machine is set to idle, the process yield and processing cost attributes are updated, and the jobs are scheduled for transfer to the next work center as planned by the product routing array. At the end of this subroutine, the machine and logout queues are checked for work. If either queue has a job(s), the first job is removed and scheduled accordingly. The logic for this subroutine is shown in Figure 6-12.

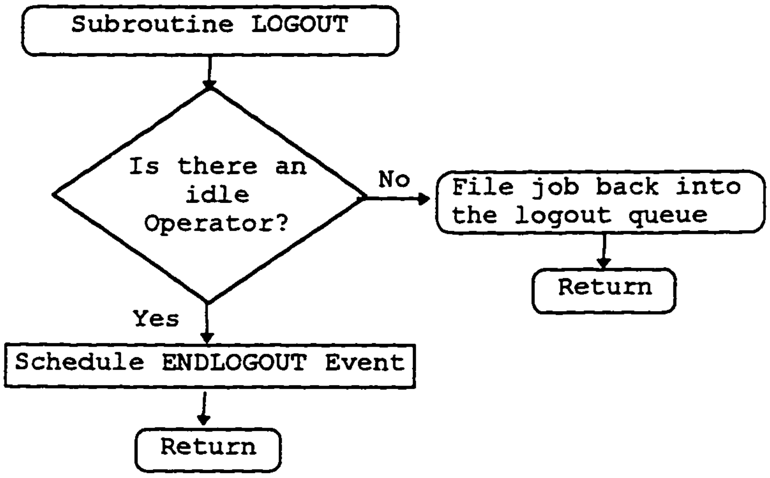


Figure 6-11: Subroutine LOGOUT Logic

The TRANSFER subroutine identifies the job's product type and current operation level (i.e., how much work has been accomplished to date). With this information the product routing array is referenced and the row reference to the process specification table is retrieved. From the process specification table, the next work center and processing requirements are identified, the job's operations number is incremented by one, and the job is scheduled for setup at the next work center. If the job is complete with all processing requirements, statistics are collected on the job, and the job is removed from the shop. Figure 6-13 shows the logic flow for the transfer subroutine.

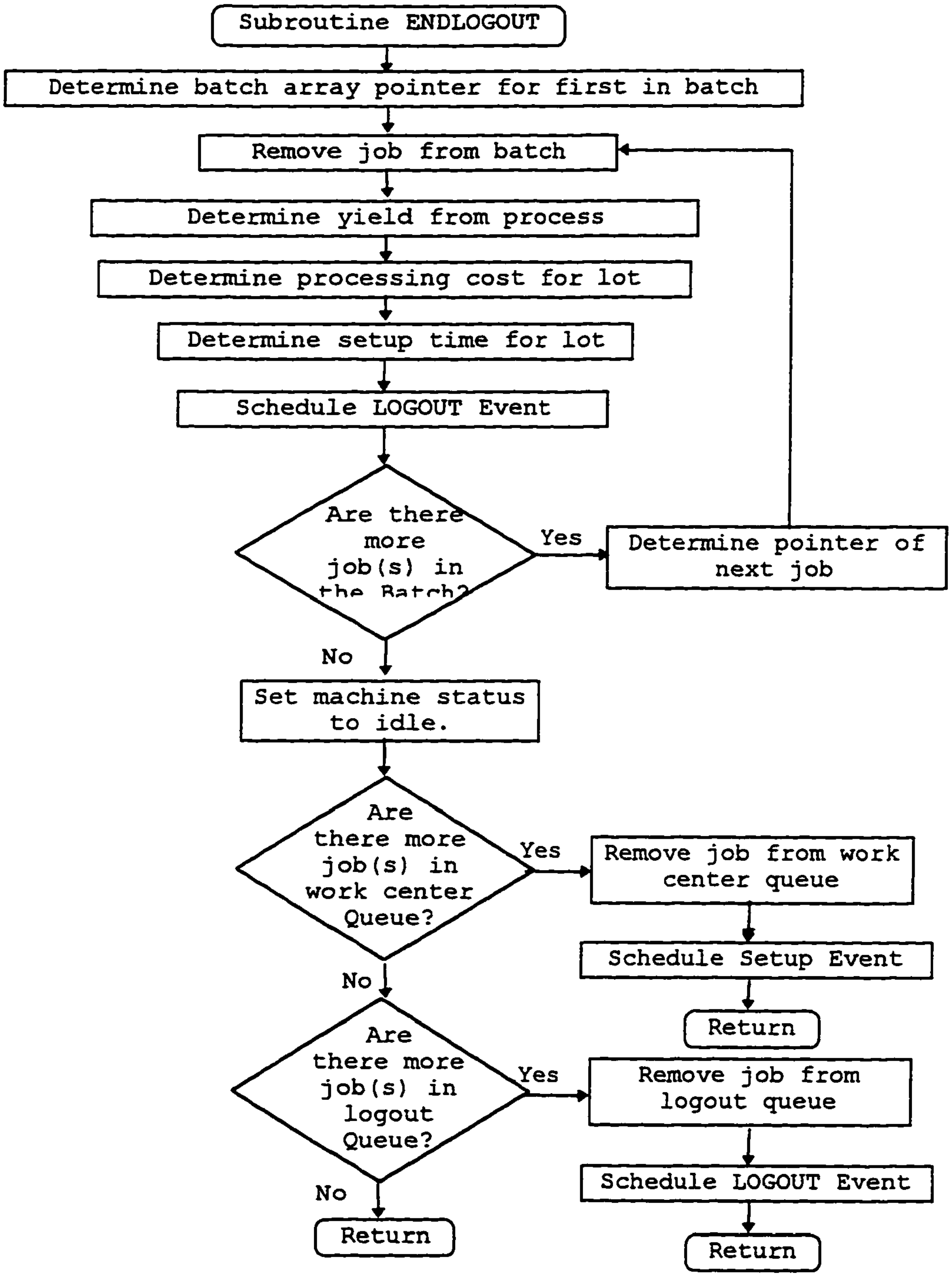


Figure 6-12: Subroutine ENDLOGOUT Logic

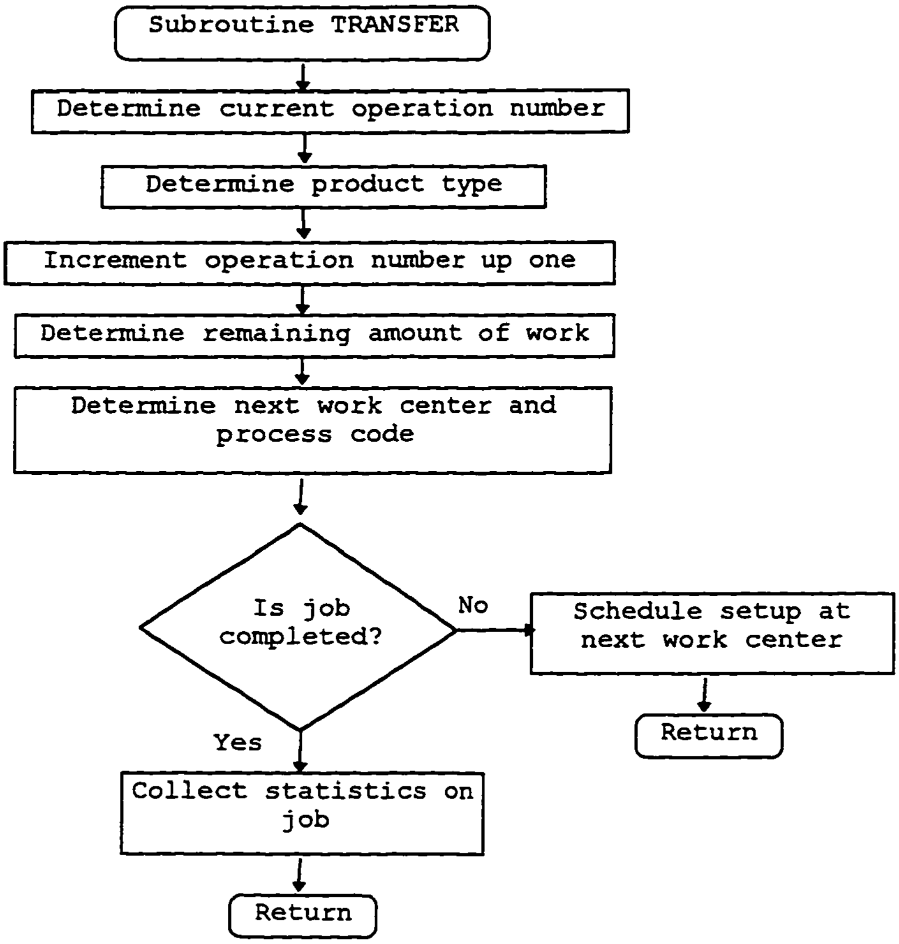


Figure 6-13: Subroutine TRANSFER Logic

The last subroutine is the output subroutine. This subroutine is called at the end of the simulation run. The purpose of this subroutine is to print out any information that is not part of the end of run summary report that is provided by the Slam II System.

6.3. Summary

In Chapter 5, analytical models where developed from theory for the prediction of various operating expenses and revenue generation. This chapter has described the production data collected at Texas Instruments' Lubbock plant and the development of a simulation model of the process utilized at the same Texas Instruments' plant.

The data collected represented the total quarterly operating expenses for the CMOS group within the Texas Instruments' Lubbock plant. These data were allocated to seventeen separate cost categories. Of these seventeen categories, fourteen were directly associated with the production process and three were accounting/financial oriented expenses.

The simulation model developed to validate the theoretical constructs proposed in Chapter 5 is a discrete event, stochastic model implemented in SLAM II. The simulation will be executed on a DEC Alpha server utilizing a VAX/VMS operating system. The model utilizes three types of resources; operators, machines, and logout terminals. Machine availability is based upon utilization and a stochastic maintenance/breakdown schedule. The ratio of resources is 1:1:1, respectively. The output from this model will include: the total throughput for each device, the total work-in-process for each device, the total processing time used at each work center, the total setup time used at each work center, and the total logout time used at each work center. Furthermore, the model will output statistics on lots for each device type in the following areas: make time, tardiness, material release rate, production cost, and cumulative setup times. Statistics are also provided for the queues in each work center.

Chapter 7 shall discuss the analysis of both the production data and the data generated by the simulation model. In Chapter 7, hypotheses concerning the statistical significance of analytical models as predictors of actual operating expenses are presented and tested.

CHAPTER 7

THE VALIDATION PROCESS

In Chapter 6, a description of the production data available from Texas Instruments, Inc.'s Lubbock plant on their integrated circuit fabrication process was made. Chapter 6 also described the simulation model that was constructed to investigate the effects of lot size on operating expenses, cycle time, and throughput. In this chapter, the data from both the simulation and from Texas Instruments shall be analyzed. Supported by the production data, the primary vehicle for this validation will be the simulation model as described in the previous chapter.

The strategy for the conduct of this analysis shall follow a multiple step process. First, the production data will be test to investigate if there is a significant difference in costs resulting from the change in lot size. Second, as discussed in Chapter 6, it will not be possible to compare the simulation results, or the analytical model results, directly to the production data. Because of this situation, if there are significant differences in the production data due to the change in lot size, a regression analysis will be conducted to identify independent operational variables that can be utilized in predicting the operational expenses for each of the simulation runs.

The third steps in this analysis will compare the analytical model results with the generated operational expenses of the simulation. The fourth step in our process will be to conduct an initial t-test of the analytical model costs with the simulation model costs. Should there be significant differences in these costs, the fifth step will be to fit the analytical model to the simulation data. The last step in our process shall be to run a t-test on the fitted analytical model costs and the simulation costs. Steps four, five, and six will be performed on the production costs, overhead costs, and the setup costs models.

7.1 The Validation Process

By utilizing the production data collected in Chapter 6, costs can be extrapolated from the results of the simulation. The independent variable of interest in the analysis is lot size. By varying the lot size of the three products used in the simulation, changes in the dependent variables (production cost, overhead cost, setup cost, and net profits) can be investigated. The following lot sizes were investigated by the simulation: 48, 24, 12, 6, and 3 units per lot. The reasoning for these lot sizes is that, prior to the first quarter of 1993, the standard lot size used at the Texas Instruments, Inc.'s Lubbock plant was 48 wafers per lot. After the first quarter of 1993, the standard lot size was changed to 24 wafers per lot. The remaining lot sizes were chosen by halving the previous lot size.

As discussed in previous chapters, it is believed that as the lot size decreases good things will happen to the production process. Three of these good things are: cycle time will decrease, work-in-process inventory levels will decrease, and overhead costs will decrease. Other related impacts (through the load utilization factor) are reductions in production costs and setup costs. From the literature reviewed in Chapter 2, there is reason to believe that the benefits derived from reductions in lot size will have a lower limit. Lot sizes below this lower limit could adversely affect the production process.

7.1.1 Evaluation of the Production Data

In section 6.1.1.2 of the previous chapter, actual operating expenses where collected from the Texas Instruments, Inc.'s Lubbock plant's CMOS group, by calendar quarters starting with the first quarter of 1992 through the last quarter of 1996. These expenses have been separated into seventeen different categories: materials, inventory deltas, cost adjustments, direct labor, indirect labor, benefits, supplies, repair and maintenance, sundries, depreciation, lease, taxes, occupancy, utilities, computer paper, other services, and other income and expenses. These expenses represent the total operating expenses incurred in each quarter of the five-year period between 1992 and 1996, at the Lubbock plant. Because of the proprietary nature of these expenses, Texas Instruments has requested that these data not be published. Their request has been honored. An analysis shall be conducted on this data to ascertain if there are any differences in the operating expenses associated with the 48 wafer lot size and the 24 wafer lot size.

7.1.1.1 Tests of the Production Data. The following hypothesis is posed to investigate if there was an affect on operating expenses due to the change in lot size.

Hypothesis 1:

Ho_1: The operating expense pools at 48 units per lot are equal to the operating expense pools at 24 units per lot,

versus the alternative hypothesis,

Ha_1: The operating expense pools at 48 units per lot are not all equal to the operating expense pools at 24 units per lot.

To test hypothesis 1, a statistical analysis was performed on the quarterly data collected. The first question of interest is to determine if there is a difference in the operating expenses associated with the two different lot sizes. An ANOVA procedure is employed to compare the means of the production data at the two different lot sizes. The results of the ANOVA procedure are shown in Table 7-1. From these results it can be seen that at the 0.05 percent level of significance there are several expense categories that are significantly affected by changes in lot size. The term 0.05 percent level of significance is defined as meaning the maximum level of probability at which a true null hypothesis could be rejected (Conover, 1980). Thus, we can reject the null hypotheses, there is a significant difference in operating expenses due to changes in production lot sizes. At the 0.05 level, seven of the sixteen expense categories were significantly affected by the change in lot size. At the 0.10 level, nine of the sixteen expense categories were significantly affected.

Table 7-1: ANOVA of TI Quarterly Operating Expenses

Dep Variable	Ind Var.	R-Sq	DF	ANOVA SS	Mean Sq.	F Val	Pr > F
Materials	Lot size	0.1509	1	7.9387E+12	7.9387E+12	3.20	0.0905
Inv. Delta	Lot size	0.05256	1	2.6643E+12	2.6643E+12	1	0.3309
Adj. Costs	Lot size	0.00011	1	2.3632E+8	2.3632E+8	0.00	0.9653
Dir. Labor	Lot size	0.00932	1	7.3689E+9	7.3689E+9	0.17	0.6855
Ind. Labor	Lot size	0.41387	1	2.6774E+12	2.6774E+12	12.71	0.0022
Benefits	Lot size	0.48101	1	1.2227E+12	1.2227E+12	16.68	0.0007
Supplies	Lot size	0.39407	1	1.4688E+12	1.4688E+12	16.68	0.0007
Repr & Maint	Lot size	0.25093	1	5.8060E+11	5.806E+11	6.03	0.0245
Sundry	Lot size	0.04231	1	1.3566E+10	1.3566E+10	0.80	0.3843
Depreciation	Lot size	0.13281	1	8.2561E+12	8.2561E+12	2.76	0.1142
Lease	Lot size	0.19716	1	1.4552E+9	1.4552E+9	4.42	0.0498
Taxes	Lot size	0.38746	1	4.4476E+9	4.4476E+9	11.39	0.0034
Occupancy	Lot size	0.09155	1	7.4062E+9	7.4062E+9	1.81	0.1947
Utilities	Lot size	0.19106	1	1.5853E+9	1.5853E+9	4.25	0.0540
Comp. Paper	Lot size	0.21389	1	1.3196E+8	1.3196E+8	4.90	0.0401
Services	Lot size	0.02186	1	1.7507E+11	1.7507E+7	0.40	0.5338

The second question of interest in this study was to determine if these costs could be predicted using the operational parameters of lot size and cycle time. To conduct this analysis, the data were converted into costs per lot. The number of lots for a given quarter was determined by adding the end-of-period work-in-process to the total throughput for the period, then dividing by the standard lot size used for that period.

In cost accounting, when a regression is performed on the firm's operating expenses, the direct production costs incurred by the firm are associated with the variable parameters, and the indirect costs, or overhead, are associated with the fixed parameter of the regression. Depending upon how the firm's expenses are categorized, some of the cost categories, in total are associated with direct costs and some are associated only with indirect

Examples of these types of categories in Texas Instruments' costs are material costs and sundry costs. The material costs are associated only with production, because these costs are due to the procurement of raw materials for production. The sundry costs are associated only with indirect expenses, because these costs are due to personnel travel.

Using the regression procedure in SAS, the results in Table 7-2 were obtained. The best fitting models for this analysis did not have an intercept. In order to interpret the result with respect to direct and indirect costs, lot size would be considered the predictor of direct costs for those categories that are associated with both direct and indirect costs, and cycle time would be considered the predictor of indirect costs. It can be seen from the results displayed in Table 7-2 that lot size and cycle time are both strong predictors of operating expenses.

A regression was also performed on the per unit costs for each quarter. Using the same operational parameters as the independent variable of the regression, Table 7-3 shows the results of this analysis.

Table 7-2: Regression Analysis of TI Quarterly Cost per Lot

Dependent Variable	**Adj. R-Sq**	**Source**	**DF**	**SS**	**MS**	**Prob > F**	**Indep. Variables**	**Prob > T**
Matls	0.9489	Model	3	5.704E+7	1.901E+7	0.0001	Lot size	0.0748
		Error	17	2.59E+6	1.523E+5		Cycle time	0.0052
		Total	20	5.963E+7			Cycle time^2	0.0002
Inv. Delta	0.1848	Model	2	1.043E+6	5.219E+5	0.0616	Lot size	0.0273
		Error	18	2.875E+6	1.59E+5		Cycle time	0.0380
		Total	20	3.919E+6				
Adjusted Costs	-0.053	Model	1	814.58	814.5	0.8384	Intercept	0.8619
		Error	18	3.425E+5	19031.5		Cycle time	0.8384
		Total	19	3.433E+5				
Direct Labor	0.9846	Model	3	6.747E+6	2.249E+6	0.0001	Lot size	0.0001
		Error	17	89600	5270.5		Cycle time	0.0545
		Total	20	6.836E+6			Cycle time^2	0.0001
Indirect Labor	0.9615	Model	3	1.052E+7	3.509E+6	0.0001	Lot size	0.0518
		Error	17	3.56E+5	20966.0		Cycle time	0.0005
		Total	20	1.088E+7			Cycle time^2	0.0001
Benefits	0.9773	Model	3	1.012E+7	3.373E+6	0.0001	Lot size	0.0098
		Error	17	1.994E+5	11732.8		Cycle time	0.0002
		Total	20	1.032E+7			Cycle time^2	0.0001
Supplies	0.9750	Model	3	1.397E+7	4.657E+6	0.0001	Lot size	0.0034
		Error	17	3.030E+5	17828.0		Cycle time	0.0013
		Total	20	1.427E+7			Cycle time^2	0.0001
Repair & Maint.	0.9771	Model	3	6.707E+6	2.235E+6	0.0001	Lot size	0.0001
		Error	17	1.332E+5	7837.2		Cycle time	0.0090
		Total	20	6.840E+6			Cycle time^2	0.0001
Sundry	0.7800	Model	1	1.001E+5	1.001E+5	0.0001	Lot size	0.0001
		Error	19	26463.4	1392.8			
		Total	20	1.266E+5				
Depre-ciation	0.8801	Model	2	3.833E+7	1.916E+7	0.0001	Cycle time	0.0001
		Error	18	4.636E+6	2.576E+5		Cycle time^2	0.0039
		Total	20	4.297E+7				
Lease	0.4574	Model	2	429.098	214.549	0.0016	Cycle time	0.0018
		Error	18	409.598	22.755		Cycle time^2	0.0108
		Total	20	838.696				
Taxes	0.9360	Model	1	11611.23	11611.23	0.0001	Lot size	0.0001
		Error	19	751.14	39.53			
		Total	20	12362.38				
Occupancy	0.9714	Model	3	2.124E+5	70831.62	0.0001	Lot size	0.0246
		Error	17	5293.73	311.39		Cycle time	0.0019
		Total	20	2.177E+5			Cycle time^2	0.0002
Utilities	0.9826	Model	3	9.360E+5	3.120E+5	0.0001	Lot size	0.0004
		Error	17	14030.1	825.30		Cycle time	0.0029
		Total	20	9.501E+5			Cycle time^2	0.0001
Lint Free Paper	0.9707	Model	3	1514.90	504.96	0.0001	Lot size	0.0141
		Error	17	38.71	2.27		Cycle time	0.0013
		Total	20	1553.62			Cycle time^2	0.0001
Services	0.7050	Model	3	1.877E+6	6.257E+5	0.0001	Lot size	0.1737
		Error	17	6.283E+5	36963.0		Cycle time	0.6371
		Total	20	2.505E+6			Cycle time^2	0.1089

Table 7-3: Regression Analysis of TI Quarterly Cost per Unit

Dependent Variable	Adj. R-Sq	Source	DF	SS	MS	Prob > F	Indep. Variables	Prob>T
Matls	0.9350	Model	2	79061.4	39530.7	0.0001	Cycle time	0.0001
		Error	18	4911.6	272.8		Cycle time^2	0.0001
		Total	20	83973.1				
Inv. Delta	0.0113	Model	2	633.6	316.8	0.3527	Intercept	0.1566
		Error	17	4858.2	285.7		Cycle time	0.1556
		Total	19	5491.8			Cycle time^2	0.1570
Adjusted Costs	-0.046	Model	1	1.7	1.7	0.7042	Intercept	0.7208
		Error	18	207.5	11.5		Cycle time	0.7042
		Total	19	209.2				
Direct Labor	0.9677	Model	2	8360.3	4180.1	0.0001	Cycle time	0.0001
		Error	18	250.6	13.9		Cycle time^2	0.0001
		Total	20	8610.9				
Indirect Labor	0.9472	Model	2	15153.1	7576.5	0.0001	Cycle time	0.0001
		Error	18	755.9	41.9		Cycle time^2	0.0001
		Total	20	15909.0				
Benefits	0.9632	Model	2	13953.8	6976.9	0.0001	Cycle time	0.0001
		Error	18	478.1	26.6		Cycle time^2	0.0001
		Total	20	14432.0				
Supplies	0.9577	Model	2	19097.7	9548.8	0.0001	Cycle time	0.0001
		Error	18	756.4	42.0		Cycle time^2	0.0001
		Total	20	19854.1				
Repair & Maint.	0.9569	Model	2	8987.0	4493.5	0.0001	Cycle time	0.0001
		Error	18	362.3	20.1		Cycle time^2	0.0001
		Total	20	9349.3				
Sundry	0.7146	Model	2	102.31	102.3	0.0001	Cycle time	0.0009
		Error	18	40.2	2.1		Cycle time^2	0.0503
		Total	20	142.5				
Depre-ciation	0.8591	Model	2	55254.9	27627.5	0.0001	Cycle time	0.0001
		Error	18	8026.4	445.9		Cycle time^2	0.0001
		Total	20	63281.4				
Lease	0.4720	Model	2	0.7586	0.3793	0.0012	Cycle time	0.0014
		Error	18	0.6869	0.0381		Cycle time^2	0.0088
		Total	20	1.4455				
Taxes	0.9104	Model	2	11.1	5.5	0.0001	Cycle time	0.0001
		Error	18	0.9	0.05		Cycle time^2	0.0053
		Total	20	12.1				
Occupancy	0.9619	Model	2	279.8	139.9	0.0001	Cycle time	0.0001
		Error	18	9.9	0.5		Cycle time^2	0.0001
		Total	20	289.8				
Utilities	0.9695	Model	2	1209.6	604.8	0.0001	Cycle time	0.0001
		Error	18	34.1	1.9		Cycle time^2	0.0001
		Total	20	1243.7				
Comp. Paper	0.9634	Model	2	2.05	1.026	0.0001	Cycle time	0.0001
		Error	18	0.06	0.003		Cycle time^2	0.0001
		Total	20	2.12				
Services	0.7023	Model	2	2485.5	1242.7	0.0001	Cycle time	0.0002
		Error	18	909.8	50.5		Cycle time^2	0.0061
		Total	20	3395.3				

In both of the above regressions, it can be seen that cycle time is a very significant predictor of the firm's operating expenses. In Table 7-2, where the costs were allocated to the total number of lots in the system for a given period, lot size was a significant predictor of the firm's operating expenses. As mentioned earlier, lot size can be interpreted as being a fixed cost variable, and cycle time can be interpreted as being a variable cost variable. Using this interpretation, given that lot size was a significant variable in the regression of costs per lot, one would expect to find a fixed cost, or intercept, in the regression on costs when allocated on a per unit basis. Contrary to this expectation, Table 7-3 shows that cycle time, was the only significant predictor of per unit costs.

A third regression was performed on the total operating expenses, as opposed to the individual operating expense categories in the previous two regressions. In this analysis, three different models were used, so as to determine which group of independent variables would provide the best prediction of overall operating expense in each of the simulation runs. The results of this analysis are found in Table 7-4.

Table 7-4: Regression Analysis of TI Total Costs

Dep. Variable	**Adj. R-Sq**	**Source**	**DF**	**SS**	**MS**	**Prob > F**	**Indep. Variables**	**Prob > T**
Total Quarterly Cost (model 1)	0.9708	Model	2	1.3556	6.778	0.0001	Cycle time	0.0001
		Error	18	3.6624	2.034		Cycle time^2	0.0001
		Total	20	1.3923				
Total Annual Costs (model 2)	0.9905	Model	3	1.273E17	3.18E16	0.0001	Lot	0.0044
		Error	14	9.287E14	7.29E13		Tput	0.0001
		Total	17	1.282E17			Tput^2	0.0042
							WIP	0.2768
Total Annual Costs (model 3)	0.9841	Model	3	1.264E17	6.32E16	0.0001	Tunits	0.0001
		Error	14	1.804E15	1.20E14		Lot	0.0116
		Total	17	1.282E17				

In the first model shown in Table 7-4, cycle time and the square of cycle time were both found to be highly significant in the prediction of total quarterly operating expenses. In the second model lot size, total system output (Tput), the square of the system's output (Tput^2), and work-in-process (WIP) were used as the independent variables. In this model all of the variables, except for WIP, were highly significant predictors. In the third model, lot size and the total number of completed production units were used as the independent variables. In the calculation of the total number of completed production units, it was assumed that WIP was evenly distributed throughout the process such that the total number of completed production units (Tunits) could be calculated as follows:

Tunits = Output + (WIP/2). Eqn. 7-1

In this third model, both lot size and tunits were highly significant predictors of total operating expenses.

An interesting result of this analysis (see the quarterly total cost model #1 in Table 7-4) is that operating expenses have a curvilinear relationship with cycle time. This relationship can be seen in Figure 7-1. As cycle time increases, we know from Little's Law, I=WT, that work-in-process (WIP) inventory levels will increase with respect to the systems total output. Since a factory will have only a finite amount of space and its processes will have a finite capacity, then as WIP increases there will be a corresponding increase in production activities, up to a point. The increase in production activity will result in an increase in operating expenses. Beyond this capacity/space-related point, there will be a decrease in production activities. With this decrease in production activities, there will also be a decrease in operating expenses. Since there is a great amount of difference in the levels of work-in-process and the output of the production system in the simulation runs, the last model (model #3), using lot size and the total number of units in the system, will be used in order to account for the costs of all units in the production system. Also, this model did not generate declining or negative operating expenses at any point.

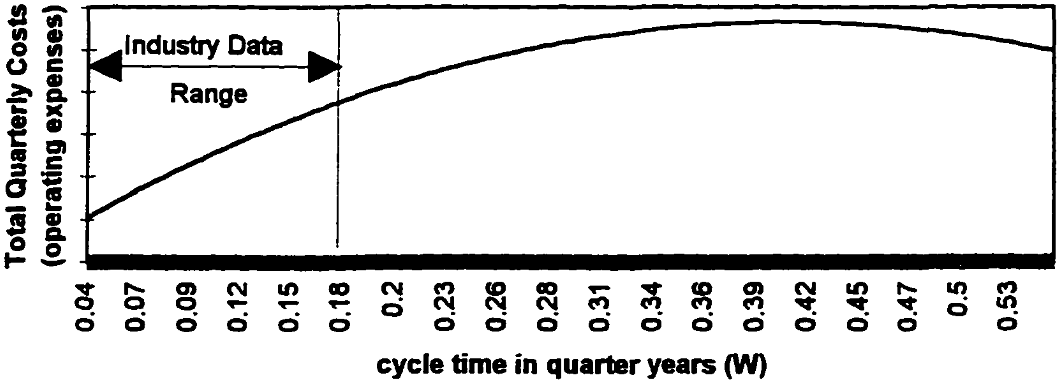


Figure 7-1: Total Quarterly Operating Expenses versus Cycle time (curve derived from Table 7-4, model 1)

7.1.2 Testing the Simulation Model

The design used for the simulation employed three devices at five different lot sizes. Based upon a factorial design analysis, holding the material release rate constant, a minimum of 75 different lot size combinations were necessary to analyze the effects of lot size on operating expenses and net profits. From the initial set of data generated, the effects of the material release rate were considered to be significant. Four levels of release rates were also investigated. A total of 290 simulations were made, resulting in eight hundred and seventy observations. Due to the limited range of the actual production data with respect to cycle times, and the significantly greater range of responses from the simulations, the simulation observations were restricted to cycle times less than 0.13 years. Due to this restriction, only three hundred and eight observations were used in the following tests of hypotheses.

7.1.2.1 Testing of Production Costs. The following hypothesis is posed to investigate if there was an affect on the production costs generated by the simulation due to the change in lot size.

Hypothesis 2:

Ho_2: The production costs at the various lot sizes are all equal,

versus the alternative hypothesis of,

Ha_2: The production costs at the various lot sizes are not all equal.

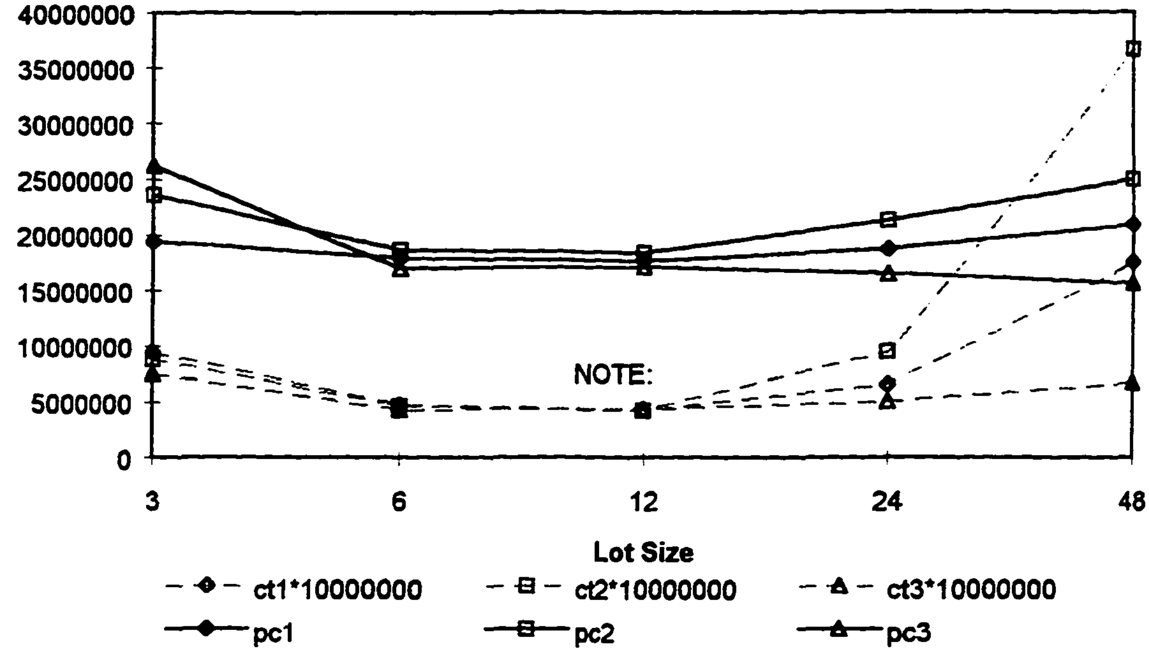
Texas Instruments has determined the per hour operating expense associated with each machine in the Lubbock plant wafer fab. As lots were moved through the simulation, each processing operation cost was accumulated on each lot. The direct support expenses not captured by the equipment hourly rates were added to this processing cost. Based upon these production costs, an ANOVA procedure was utilized to test hypothesis 2. Table 7-5 shows the results of this analysis of variance test.

Table 7-5: ANOVA Test of Simulated Production Costs

Dep Var.	**Ind Var.**	**R-Sq**	**DF**	**ANOVA SS**	**Mean Sq.**	**F Val**	**Pr > F**
Device 1	lot size	0.0155	4	1.348E16	3.370E15	3.41	0.0089
Device 2	lot size	0.0148	4	9.416E17	2.354E17	3.26	0.0115
Device 3	lot size	0.0753	4	1.346E16	3.365E15	17.63	0.0001

We can conclude from the results shown in Table 7-5 that there are significant differences in production costs at the 0.05 level of significance due to changes in lot size for each of the three devices. From the theoretical development of the analytical production cost model in Chapter 5, this result is not unexpected. As lot sizes are changed, the load utilization of the production equipment would also change. As the load capacity utilization increases, the per unit costs will decrease.

Figure 7-2 shows a plot of the production cost means from the ANOVA analysis conducted about. In this plot, it can be seen that the production cost means for all three products used in the simulation vary with lot size. The cycle times for the three products has been scaled to overlay the production cost means. By comparing the production costs against their respective cycle times, it can be seen that all three products plot along a similar trend as the cycle times. Product three tends to tail down instead of up for the lot size of 48 units. This deviations could be due to the fact that product three's upper release rate limit is near 250 units per shift, and the material release rates utilized in the simulation are significantly lower than that. Thus, it would be expected that product three would not be as responsive to changes in cycle time as the other two product.



NOTES: 1) ct# means cycle time for the jth product
2) pc# means production cost for the jth product

Figure 7-2: Production Cost Means

7.1.2.2 Testing of Overhead Costs. The following hypothesis is posed to investigate if there was an effect on the overhead costs generated by the simulation due to the change in lot size.

Hypothesis 3:

Ho_3: The overhead costs at the various lot sizes are all equal,

versus the alternative hypothesis of,

Ha_3: The overhead costs at the various lot sizes are not all equal.

Using the third model in Table 7-4, total operating expenses were calculated for one entire year. Operating expenses can be divided into two types of costs: direct and indirect. The direct costs consist of the production costs and the physical portions, labor and consumable material costs, of the setup costs.

Due the production processes used in the fabrication of integrated circuits being so highly automated, the setup process usually consists of simply loading the wafers into the machine and electronically downloading the processing recipe. The whole setup process takes about three to five minutes, and there are no materials consumed. Thus, the overhead costs for the year can be determined by subtracting the direct costs from the total operating expenses, assuming the physical setup costs to be essentially zero. Based upon these overhead costs an ANOVA procedure was utilized to test hypothesis 3. Table 7-6 shows the results of this analysis of variance test.

Table 7-6: ANOVA Test of Simulated Overhead costs

Dep Variable	Ind Variable	R-Sq	DF	ANOVA SS	Mean Sq.	F Val	Pr > F
Device 1	lot size	0.328	4	4.673E15	1.168E15	36.99	0.0001
Device 2	lot size	0.0927	4	6.597E15	1.649 E15	7.74	0.0001
Device 3	lot size	0.0679	4	2.616E15	6.540 E15	5.53	0.0003

From the results shown in Table 7-6, we can again reject the null hypothesis. There is a significant difference in overhead costs associated with changes in lot size for each of the three devices.

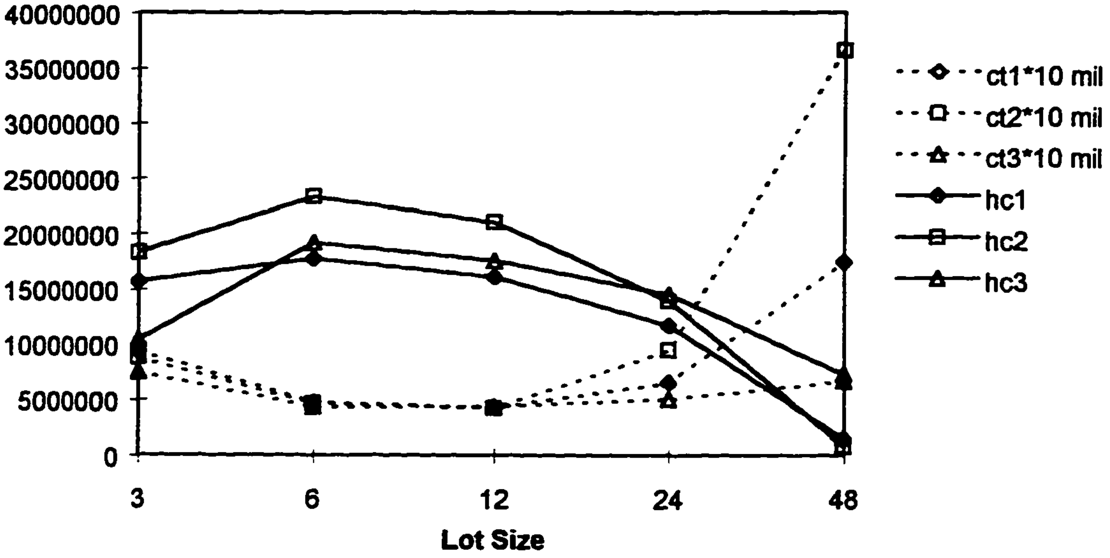


Figure 7-3: Overhead Cost Means

Figure 7-3 is a plot of the overhead cost means form the ANOVA analysis that was conducted above. As with the production costs, overhead cost both vary with lot size, and are responsive to cycle times. Again, the product cycle times have been scaled and overlaid on the plot for comparison purposes. Unlike the production cost means, the overhead cost means are indirectly related to cycle times.

7.1.2.3 Testing of Setup Costs. The following hypothesis is posed to investigate if there was an effect on the setup costs generated by the simulation due to the change in lot size.

Hypothesis 4:

Ho_4: The setup costs at the various lot sizes are all equal,

versus the alternative hypothesis of,

Ha_4: The setup costs at the various lot sizes are not all equal.

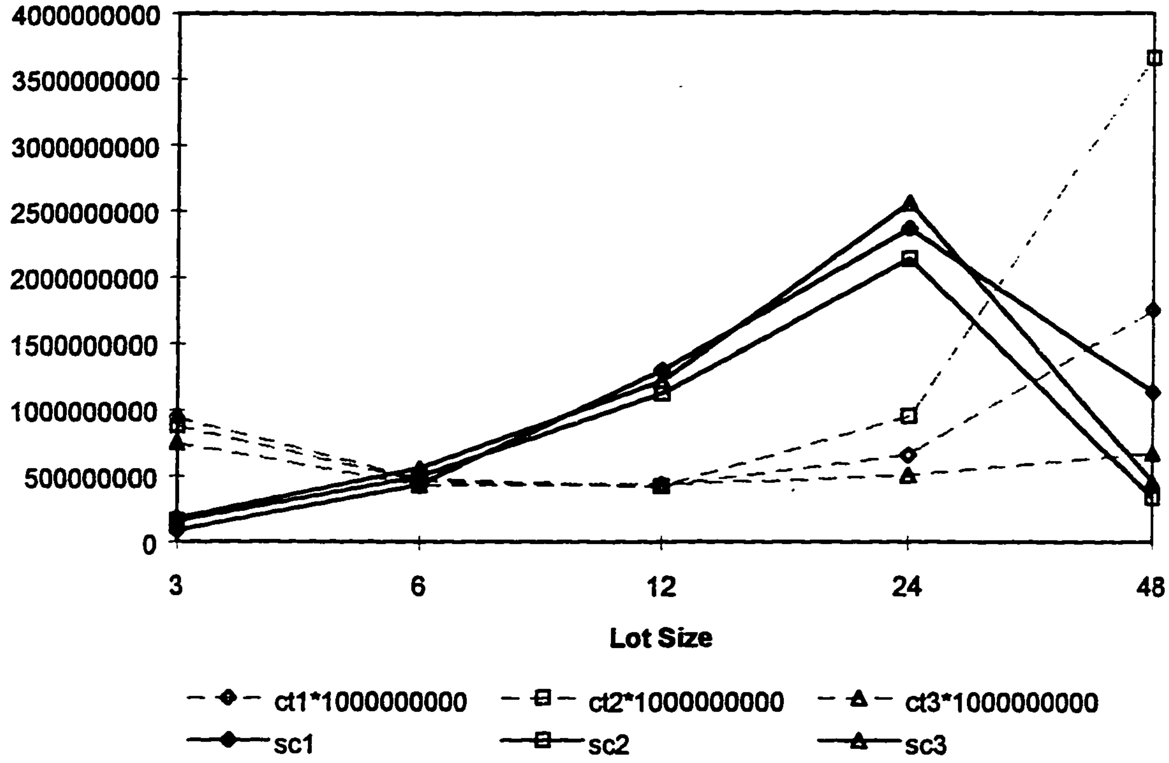
From the discussion in section 5.7, we know that there are two costs associated with setups: the physical costs of labor and materials, and the opportunity costs of lost production. We also know from the discussion in the previous section that the physical costs associated with setups in an integrated circuit fabrication process are virtually zero. Thus, the primary cost of setups is the opportunity costs of lost production at the bottleneck.

The typical selling price for a finished wafer is about $1,500.00. Using this figure, and adjusting the total throughput for yield, the revenues per device for an entire year were generated. Subtracting the derived operating expenses (generated in section 7.1.2.2) from the revenues, and dividing by the throughput plus one-half the WIP, a net profit per production unit was calculated. Given the total amount of time spent performing setups at the bottlenecking work center, and the average processing time at the bottleneck, the number of units were calculated that could have been produced with no setup time requirements. By multiplying these lost units by the expected net profit per unit, the opportunity costs due to setups was determined. Based upon these setup costs, an ANOVA procedure was utilized to test hypothesis 4. Table 7-7 shows the results of this analysis of variance test.

Table 7-7: ANOVA Test of Simulated Setup Costs

Dep Variable	**Ind Variable**	**R-Sq**	**DF**	**ANOVA SS**	**Mean Sq.**	**F Val**	**Pr > F**
Device 1	lot size	0.1057	4	7.913E16	1.978E16	8.95	0.0001
Device 2	lot size	0.0544	4	4.487E16	1.121E16	4.36	0.0019
Device 3	lot size	0.0399	4	3.668E16	9.17E16	3.15	0.0146

At the 0.05 level of significance, we reject the null hypothesis. From the results of Table 7-7, there is a significant difference in setup costs for each of the three devices due to changes in lot size. One reason for these results is due to the changes in equipment load capacity utilization, resulting from changes in lot size (reference Chapter 5, Section 3, for discussion on load capacity utilization). Another reason for these results, based on observations of the simulation runs, is that changes in lot size caused the bottlenecking work center to change.



NOTES: 1) ct# means cycle time for the jth product
2) sc# is the setup cost mean for the jth product

Figure 7-4: Setup Cost Means

Figure 7-4 is a plot of the setup cost means form the ANOVA analysis that was conducted above. As with the production costs and overhead costs, setup costs vary with lot size. Unlike both the production costs and overhead costs, setup costs are not responsive to cycle times. Instead, they appear to be response to the bottlenecks load utilization, which in turn are affected by both lot size, the bottleneck's load capacity, and the material release rate of the product. Again, the product cycle times have been scaled and overlaid on the plot for comparison purposes.

7.1.3 Comparisons between the Simulation Model and the Analytical Models

In section 7.1.1, the Texas Instruments' production data were tested to determine if there was a significant difference in operating expenses as a result of a change in lot size. Further statistical analysis resulted in a regression model for predicting these expenses. In section 7.1.2, costs were generated for each of the simulation runs using the this regression model. These generated costs were then statistically analyzed and tested to determine if there were significant differences as a result of the changes in lot size. In both sections, significant differences were found.

This section will investigate the similarities and the differences between the costs generated by the analytical constructs developed in Chapter 5 and the costs generate for each of the simulation runs. By using the framework of a t-test, hypotheses about the mean differences between the simulation model and the analytical constructs were tested. The objectives of these tests were to show that the analytical constructs will provide results that are similar to the results provided by the simulation model. Thus, we would expect to accept, or more accurately state, "fail to reject," the null hypotheses stated in sections 7.1.3.1, 7.1.3.2, and 7.1.3.3.

7.1.3.1 Comparison of Production Costs. The following hypothesis is posed to investigate similarity of production costs means between the simulation and the analytical model across due the range of lot sizes investigated.

Hypothesis 5:

Ho_5: The production costs from the simulation model at various lot sizes are equal to the production costs generated from the analytical construct at the same lot sizes,

versus the alternative hypothesis of,

Ha_5: The production costs from the simulation model at various lot sizes are not all equal to the production costs generated from the analytical construct at the same lot sizes.

From the initial t-test results comparing the production cost means, we rejected the null hypotheses. There were significant differences in the costs from the analytical production cost model and the simulation runs.

Using the PROC GLM procedure in SAS, the relationships of the various device lot sizes and material release rates were investigated. The relationships are listed in Table 7-8 below.

From the results of the analysis shown in Table 7-8, it can be seen that both lot size and material release rates are significant factors in the determination of production costs. It can also be seen that the interactions of the three devices investigated are significant factors. Thus, in order to model production costs in this system, and presumably any other production system, one should account for the interactions and material release rates for all products being produced.

Table 7-8: General Linear Model of Production Costs per Unit

Dependent Variable: PCPU1

Source	DF	SS	MS	F Value	Pr>F
Model	114	47993.22478	420.99319	218.48	0.0001
Error	193	371.90286	1.92695		
Cor. Total	307	48365.12765			

R-Square	C.V.	Root MSE	PCPU1 Mean
0.992311	1.086666	1.38814908	127.74388528

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LS1	4	1095.38328	273.84582	142.11	0.0001
LS2	4	5622.72326	1405.68081	729.48	0.0001
LS1*LS2	16	1107.70869	69.23179	35.93	0.0001
LS3	4	5022.91831	1255.72957	651.66	0.0001
LS1*LS3	16	367.36693	22.96043	11.92	0.0001
LS2*LS3	16	475.05319	29.69082	15.41	0.0001
LS1*LS2*LS3	40	1490.51807	37.26295	19.34	0.0001
REL1	4	359.80213	89.95053	46.68	0.0001
REL2	4	164.54262	41.135655	21.35	0.0001
REL3	4	92.00991	23.00247	11.94	0.0001

Dependent Variable: PCPU2

Source	DF	SS	MS	F Value	Pr > F
Model	114	10958222.0078	96124.7544	4712.86	0.0001
Error	193	3936.4783	20.3962		
Cor. Total	307	10962158.4861			

R-Square	C.V.	Root MSE	PCPU2 Mean
0.999641	2.793831	4.51622196	161.64980384

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LS1	4	297546.33569	74386.58392	3647.07	0.0001
LS2	4	212236.16441	53059.04110	2601.41	0.0001
LS1*LS2	16	649202.1096	40575.13185	1989.34	0.0001
LS3	4	215340.08125	53835.02031	2639.46	0.0001
LS1*LS3	16	1703658.27949	106478.64246	5220.50	0.0001
LS2*LS3	16	820325.84501	51270.36531	2513.71	0.0001
LS1*LS2*LS3	40	4393145.01013	109828.62525	5384.74	0.0001
REL1	4	192.63761	48.15940	2.36	0.0547
REL2	4	267.23045	66.80761	3.28	0.0126
REL3	4	2189.27943	547.31985	26.83	0.0001

Dependent Variable: PCPU3

Source	DF	SS	MS	F Value	Pr > F
Model	114	4670691.82418	40970.98091	41.07	0.0001
Error	193	192513.04234	997.47690		
Cor. Total	307	4863204.86653			

R-Square	C.V.	Root MSE	PCPU3 Mean
0.960414	24.27116	31.58285775	130.12506764

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LS1	4	134490.81831	33622.70457	33.71	0.0001
LS2	4	87697.95489	21924.48872	21.98	0.0001
LS1*LS2	16	559634.87285	34977.17955	35.07	0.0001
LS3	4	156817.36425	39204.34106	39.30	0.0001
LS1*LS3	16	853237.45399	53327.34087	53.46	0.0001
LS2*LS3	16	795732.27714	49733.26732	49.86	0.0001
LS1*LS2*LS3	40	1418238.31010	35455.95775	35.55	0.0001
REL1	4	73041.52233	18260.38058	18.31	0.0001
REL2	4	34709.64983	8677.41245	8.70	0.0001
REL3	4	99515.76000	24878.94000	24.94	0.0001

Table 7-8: continued.

NOTEs: 1 PCPU# means production cost per unit for product #.
2 LS# means lot size for product #.
3 REL# means material release rate for product #.

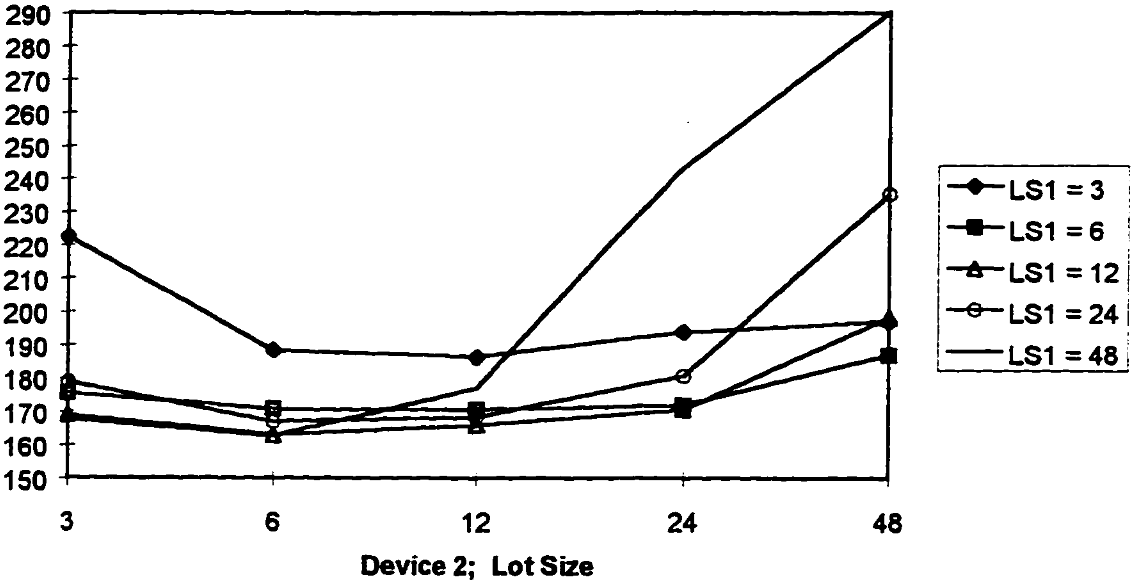


Figure 7-5: Production Costs 2-Way Interactions for Device 1

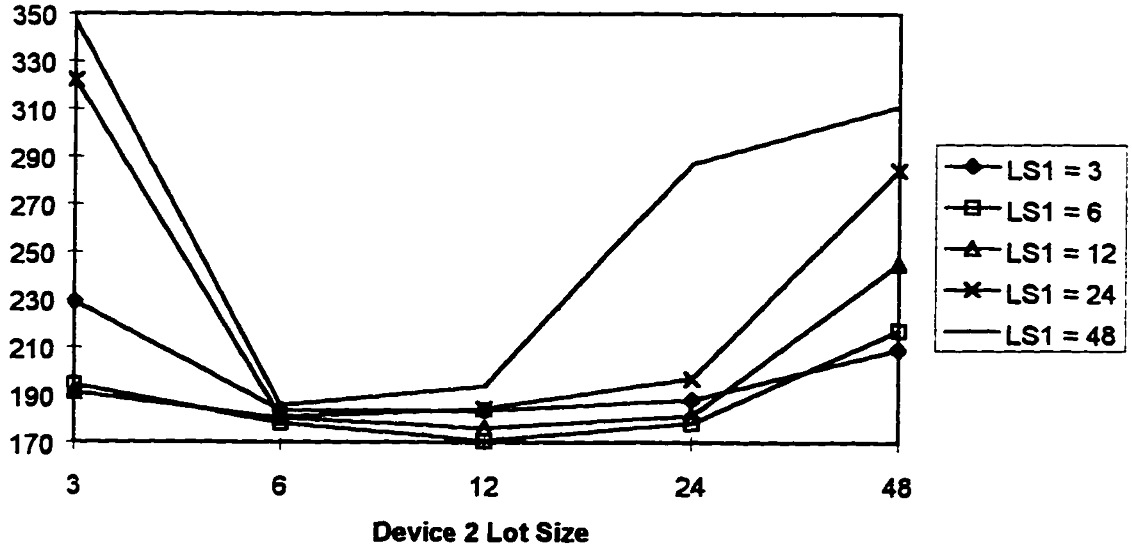


Figure 7-6: Production Costs 2-Way Interactions for Device 2

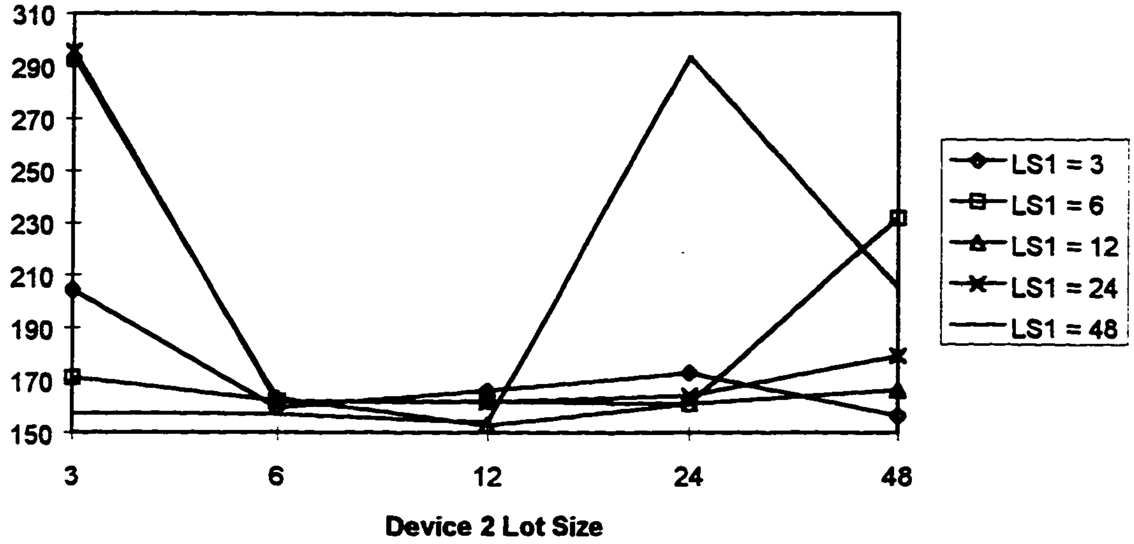


Figure 7-7: Production Costs 2-Way Interactions for Device 3

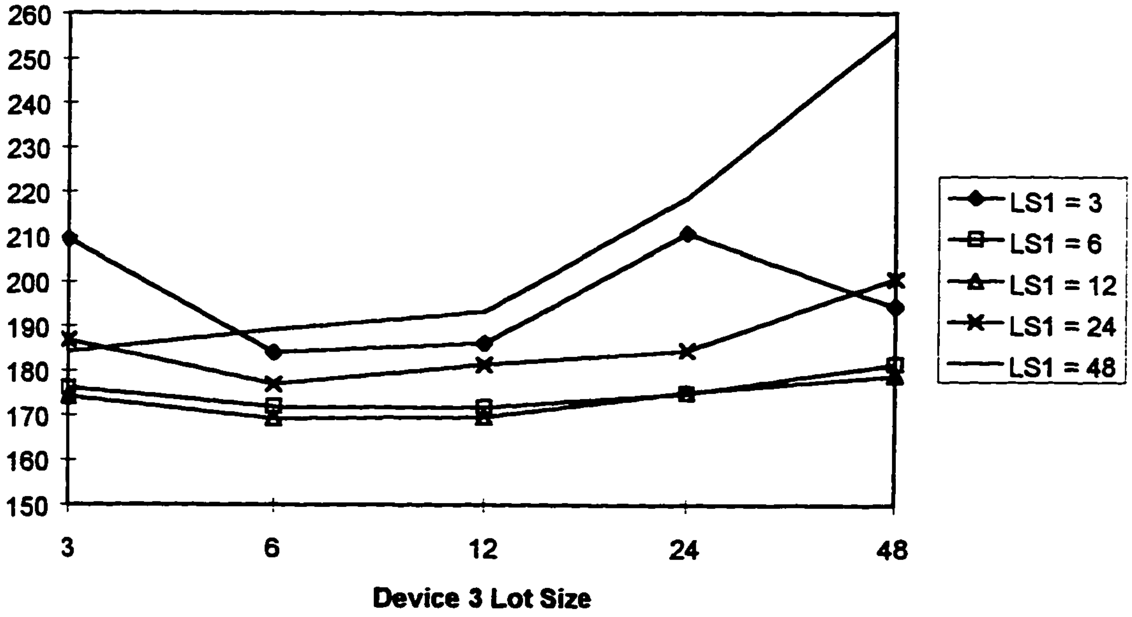


Figure 7-8: Production Costs 2-Way Interactions for Device 1

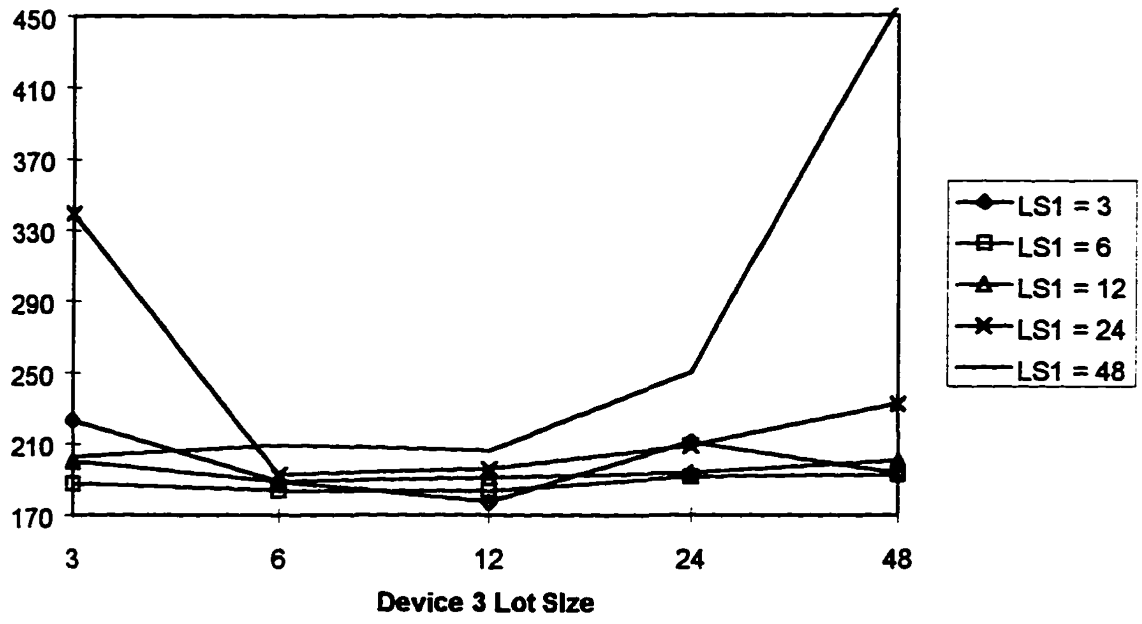


Figure 7-9: Production Costs 2-Way Interactions for Device 2

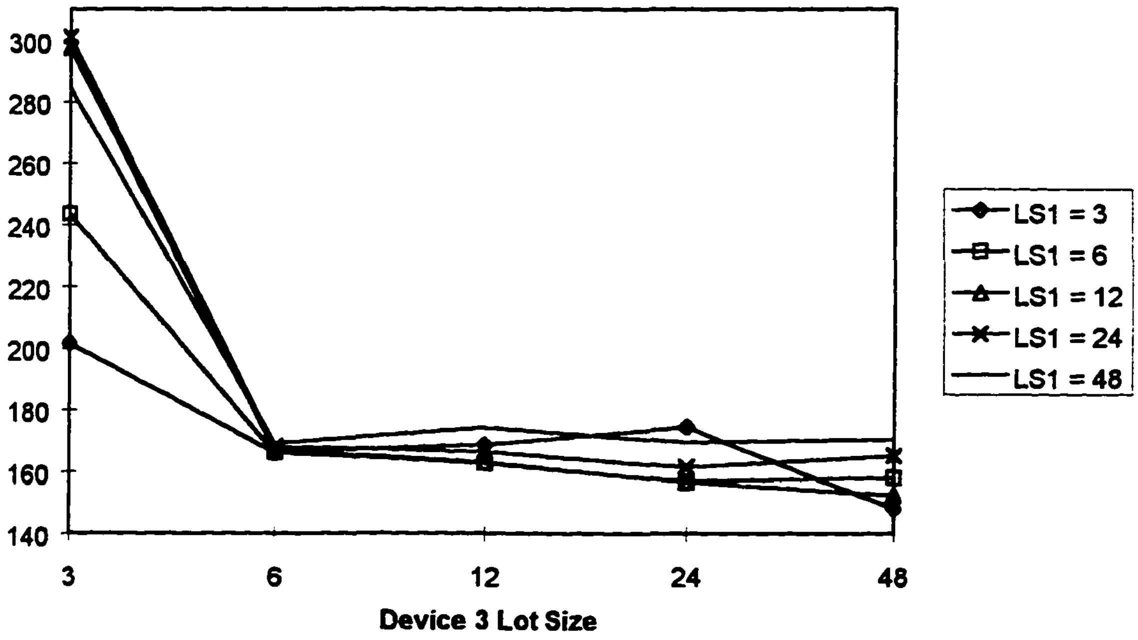


Figure 7-10: Production Costs 2-Way Interactions for Device 3

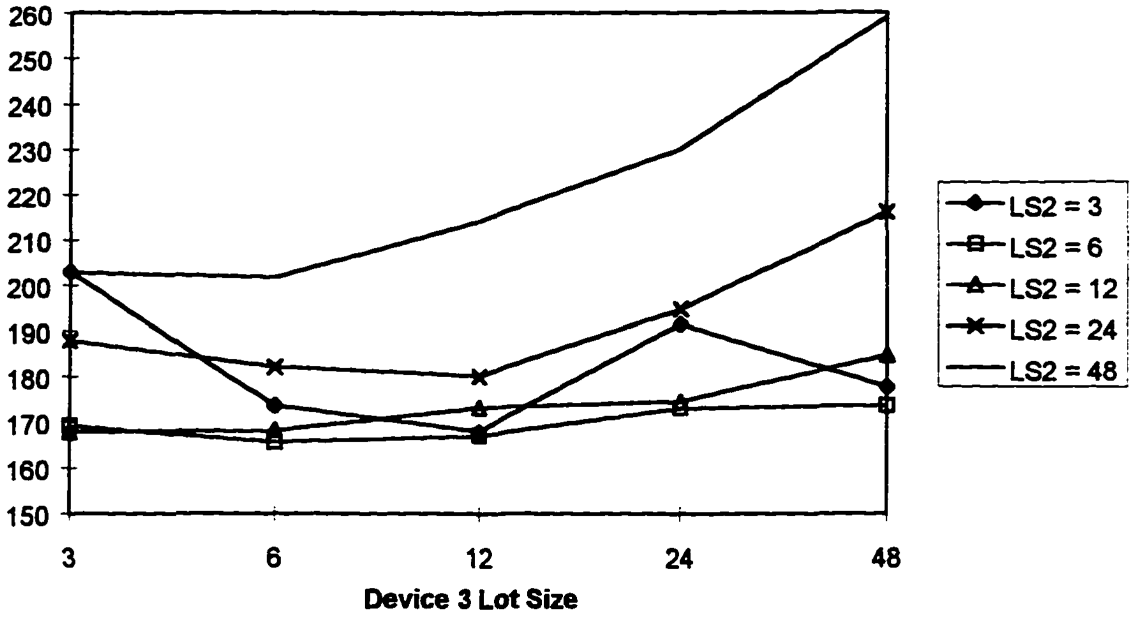


Figure 7-11: Production Costs 2-Way Interactions for Device 1

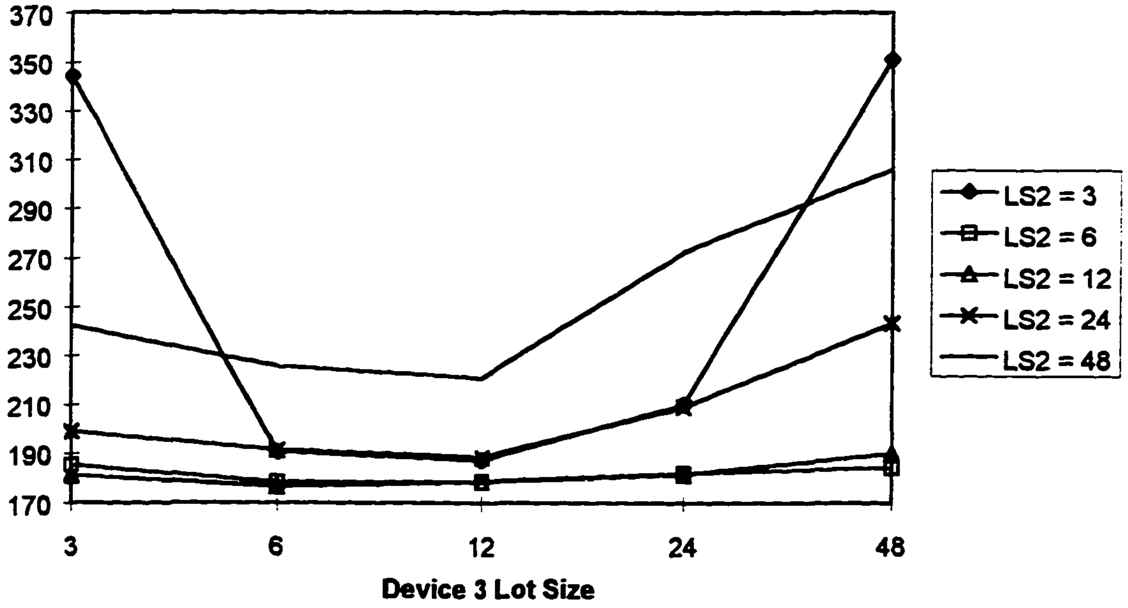


Figure 7-12: Production Costs 2-Way Interactions for Device 2

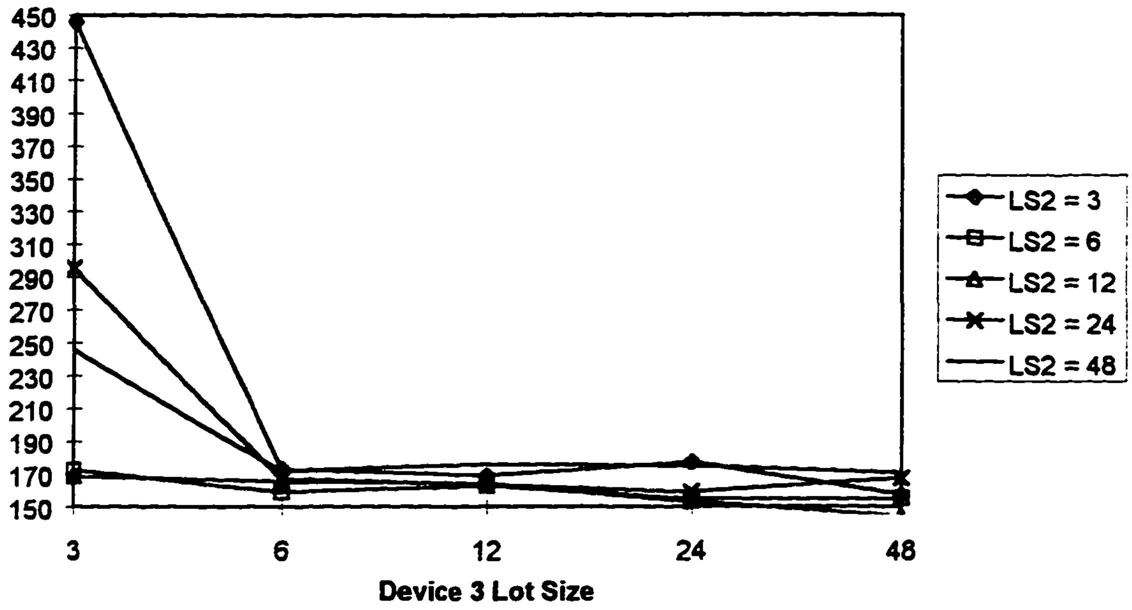


Figure 7-13: Production Costs 2-Way Interactions for Device 3

In Figures 7-5 through 7-13 the two-way interactions from Table 7-8 are plotted. In all nine figures it can be seen that the interactive affects are more prevalent for the lot sizes that tend to have the higher cycle times (i.e.; 3, 24, and 48). The production activities that are associated with these interactions are; the lot sizes of the different devices that are in production, the load capacity of the of the processing equipment, the arrival rates of product to the individual work centers, and amount of shared resources (i.e.; processing equipment) between the different products.

As has been shown in the previous discussions, lot size versus equipment load capacity versus processing time is directly related to the amount of time that a job (lot of material) will spend in a work center. The faster each job can be processed through each work center, the faster the arrival rates to the next work centers. From queuing theory, we know that as arrival rates approach service rates, the greater the utilization rate and the longer the time in system. For products who's yield rates are sensitive to cycle time, like semiconductors, long cycle times will equate to lower yields. Lower product yield rates mean that there are fewer units to absorb the costs of production. Thus, the per unit costs will increase. Also, from our previous discussion in Chapter 5 on load capacity utilization, the lower the load capacity utilization, the greater the per unit costs. The following fifteen figures are plots of the three-way interactions from Table 7-8.

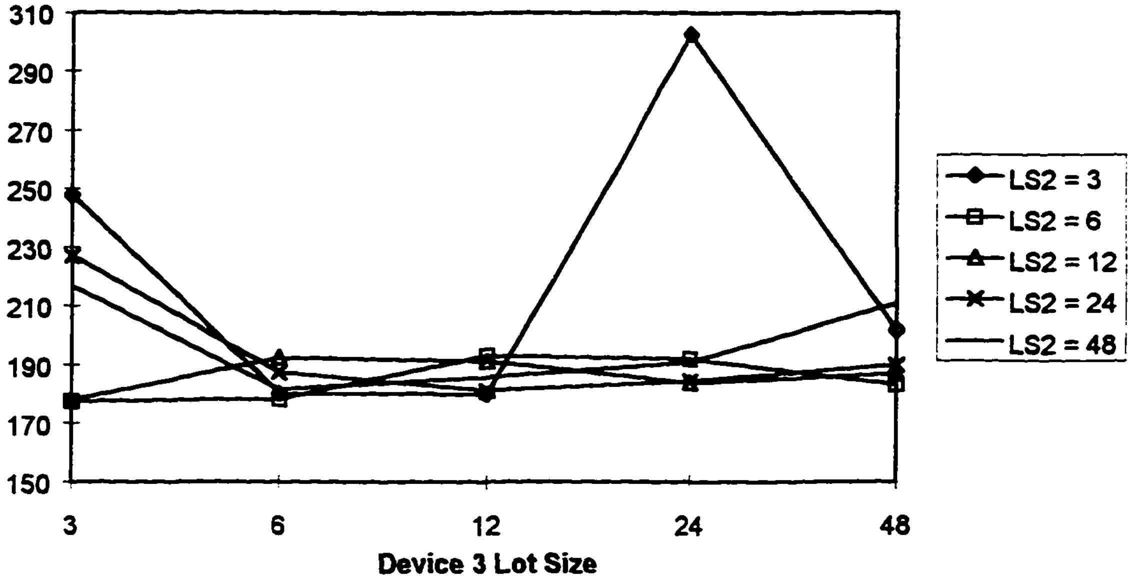


Figure 7-14: Production Costs 3-Way Interactions for Device 1, Holding Device 1 Lot Size = 3

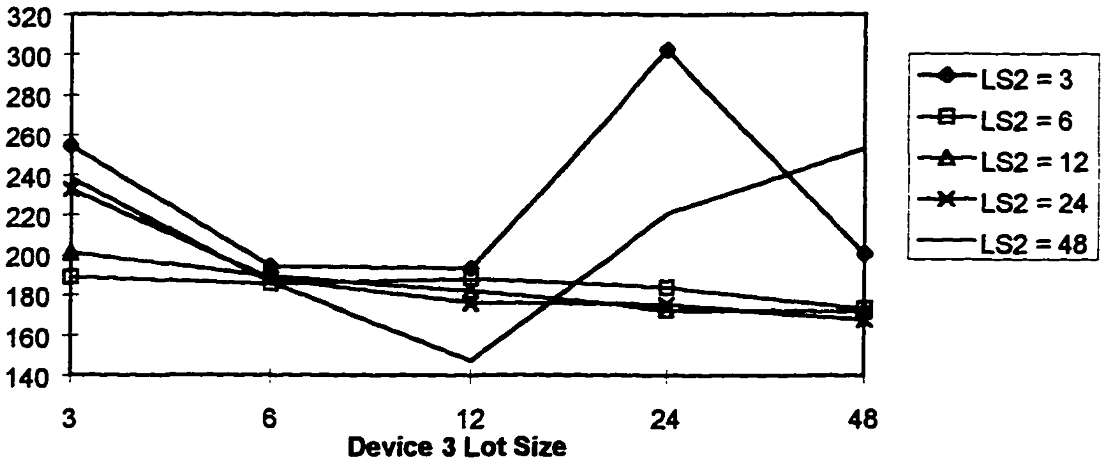


Figure 7-15: Production Costs 3-Way Interactions for Device 2, Holding Device 1 Lot Size = 3

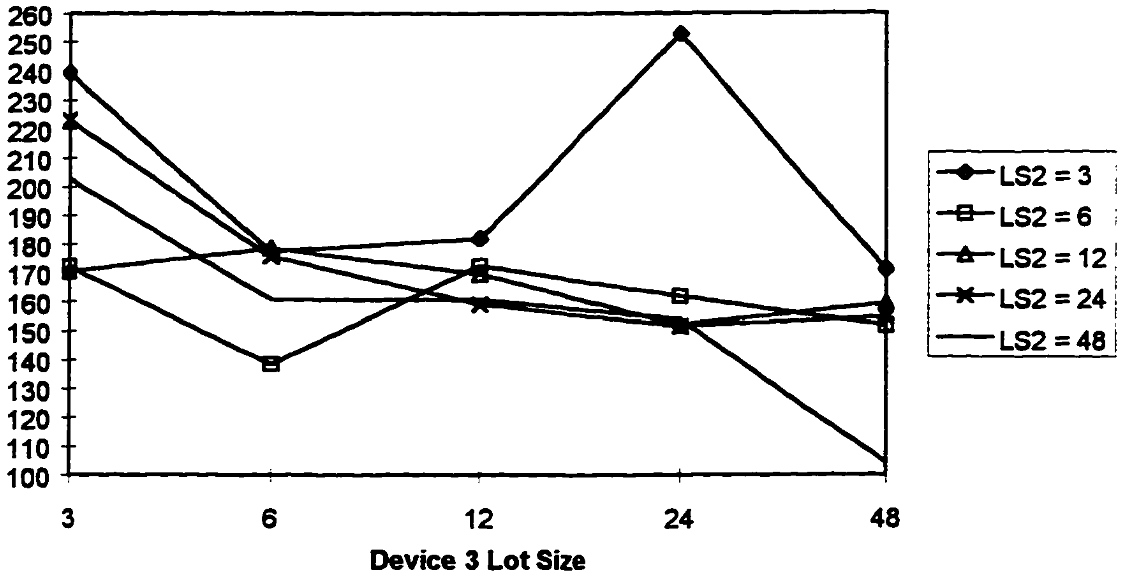


Figure 7-16: Production Costs 3-Way Interactions for Device 3, Holding Device 1 Lot Size = 3

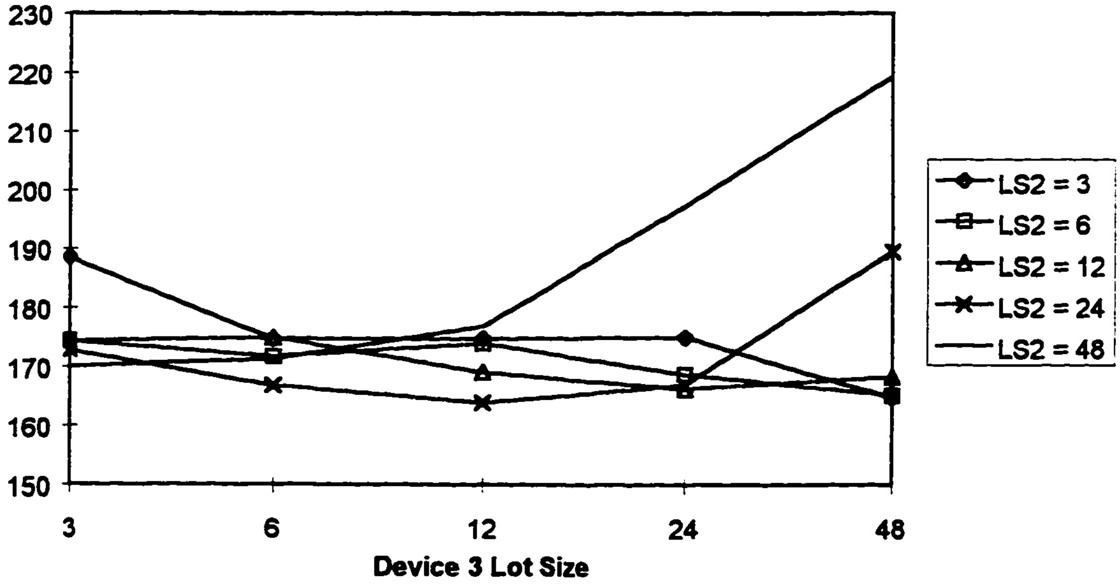


Figure 7-17: Production Costs 3-Way Interactions for Device 1, Holding Device 1 Lot Size = 6

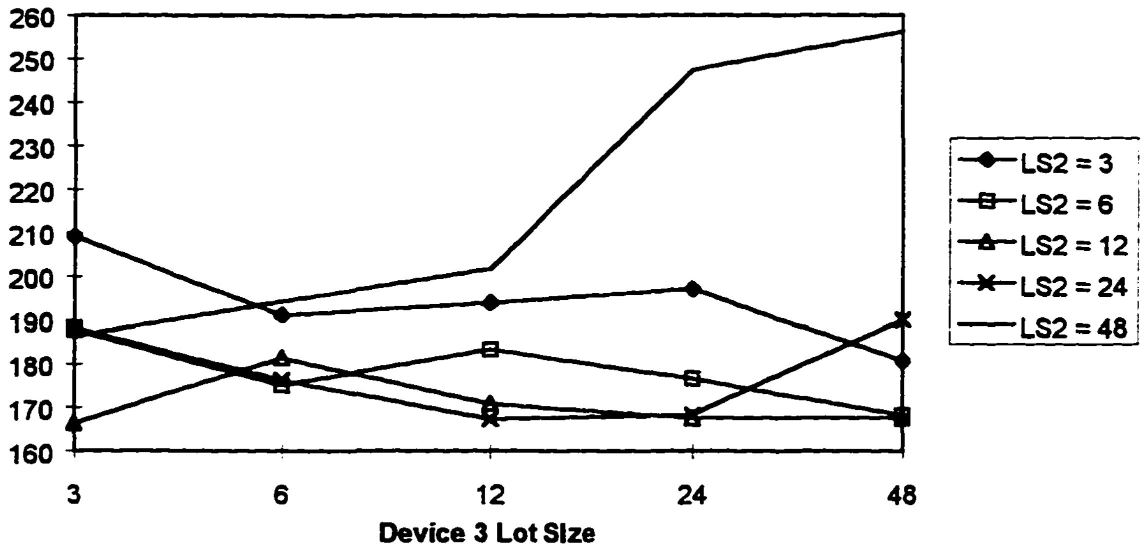


Figure 7-18: Production Costs 3-Way Interactions for Device 2, Holding Device 1 Lot Size = 6

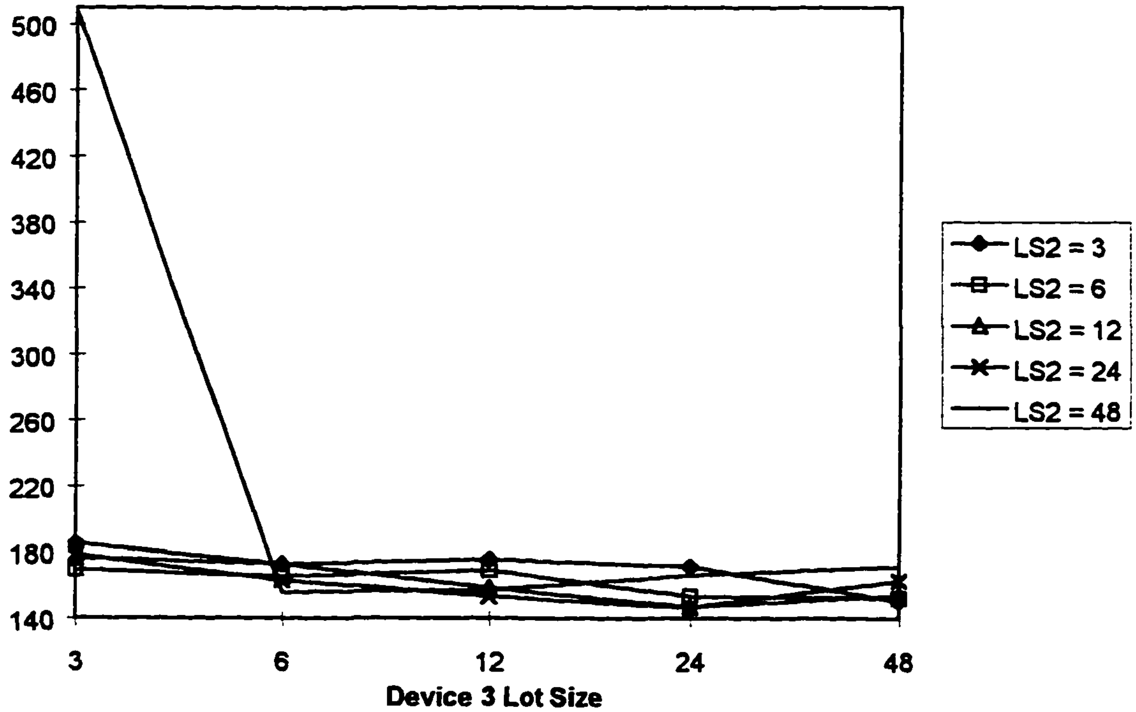


Figure 7-19: Production Costs 3-Way Interactions for Device 3, Holding Device 1 Lot Size = 6

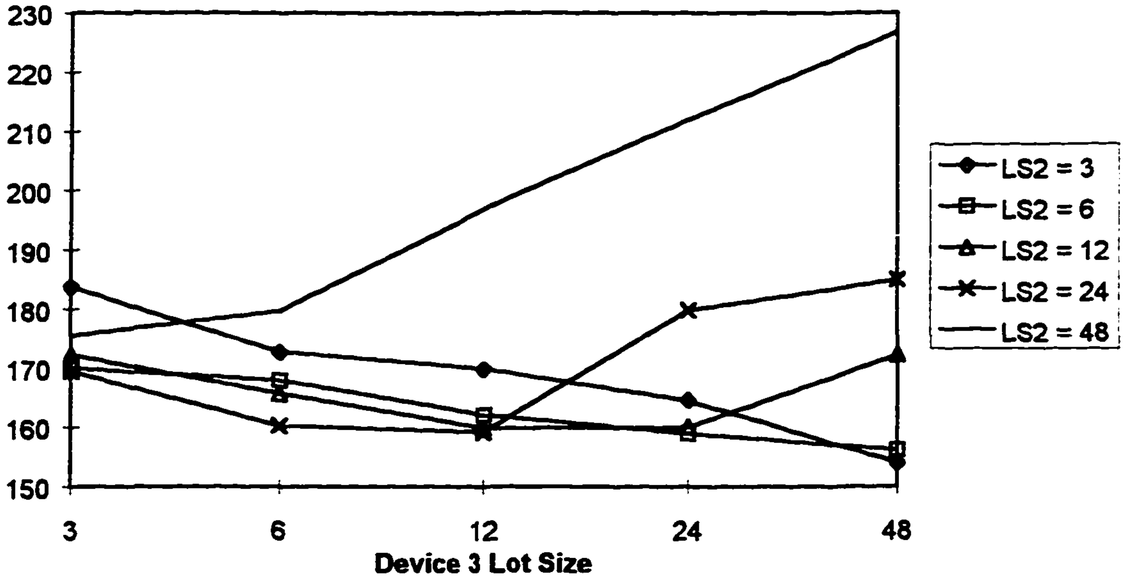


Figure 7-20: Production Costs 3-Way Interactions for Device 1, Holding Device 1 Lot Size = 12

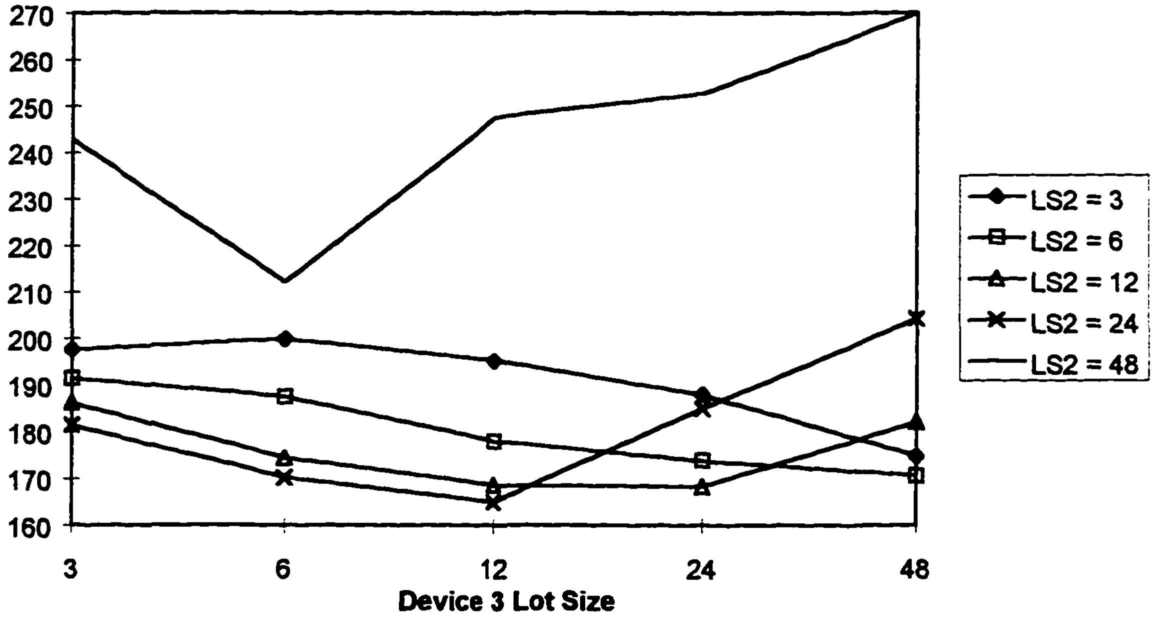


Figure 7-21: Production Costs 3-Way Interactions for Device 2, Holding Device 1 Lot Size = 12

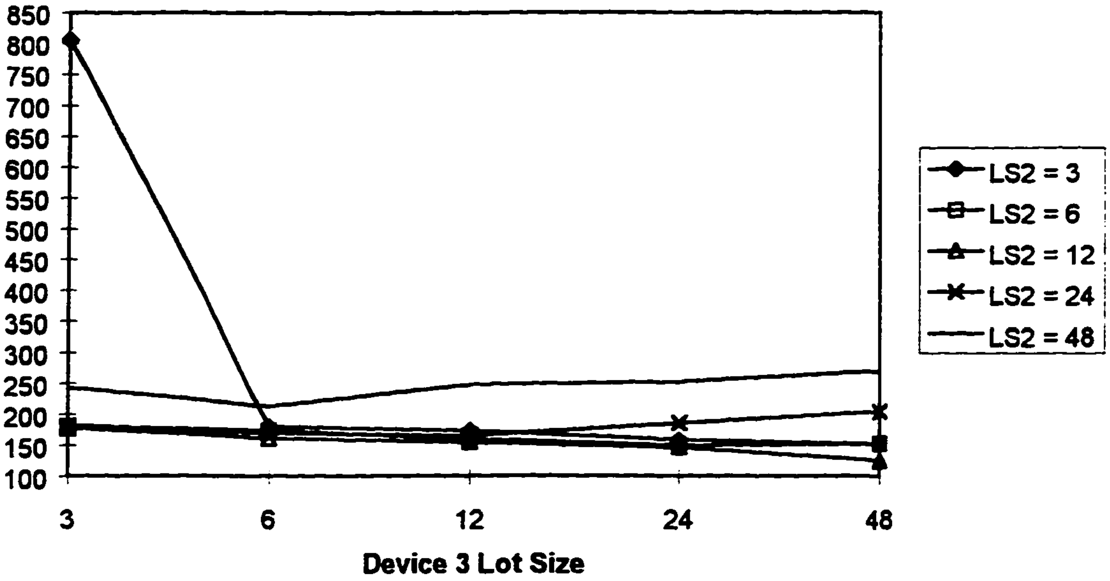


Figure 7-22: Production Costs 3-Way Interactions for Device 3, Holding Device 1 Lot Size = 12

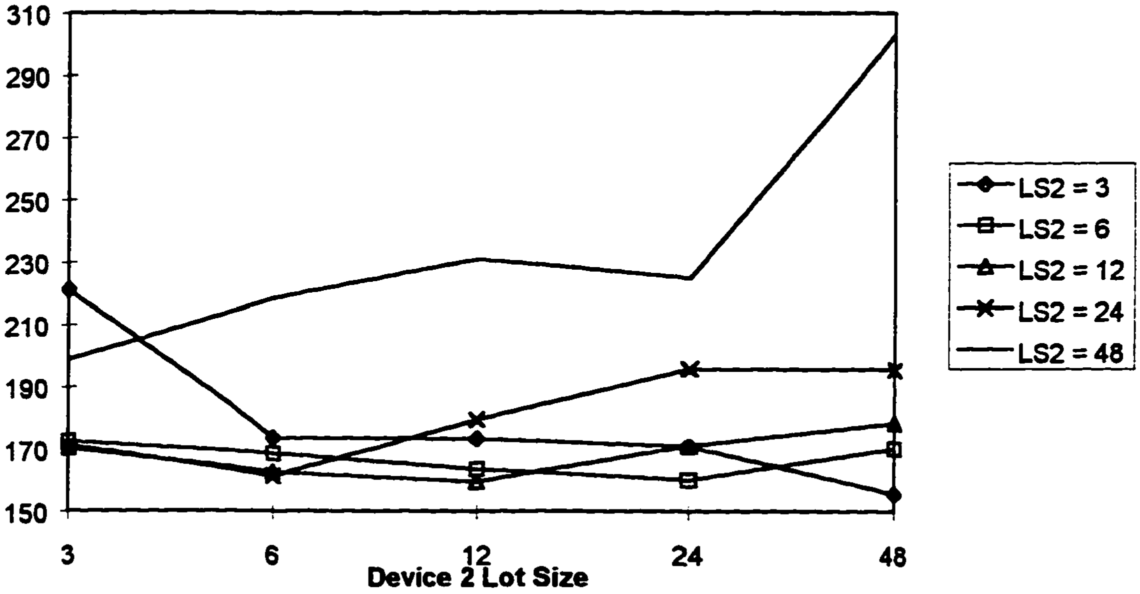


Figure 7-23: Production Costs 3-Way Interactions for Device 1, Holding Device 1 Lot Size = 24

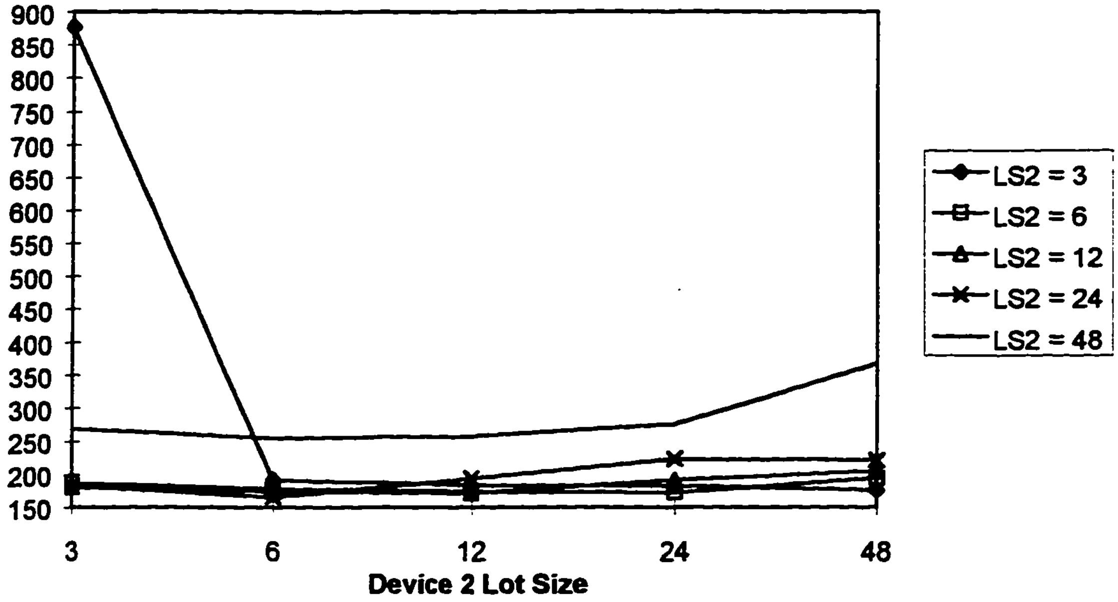


Figure 7-24: Production Costs 3-Way Interactions for Device 2, Holding Device 1 Lot Size = 24

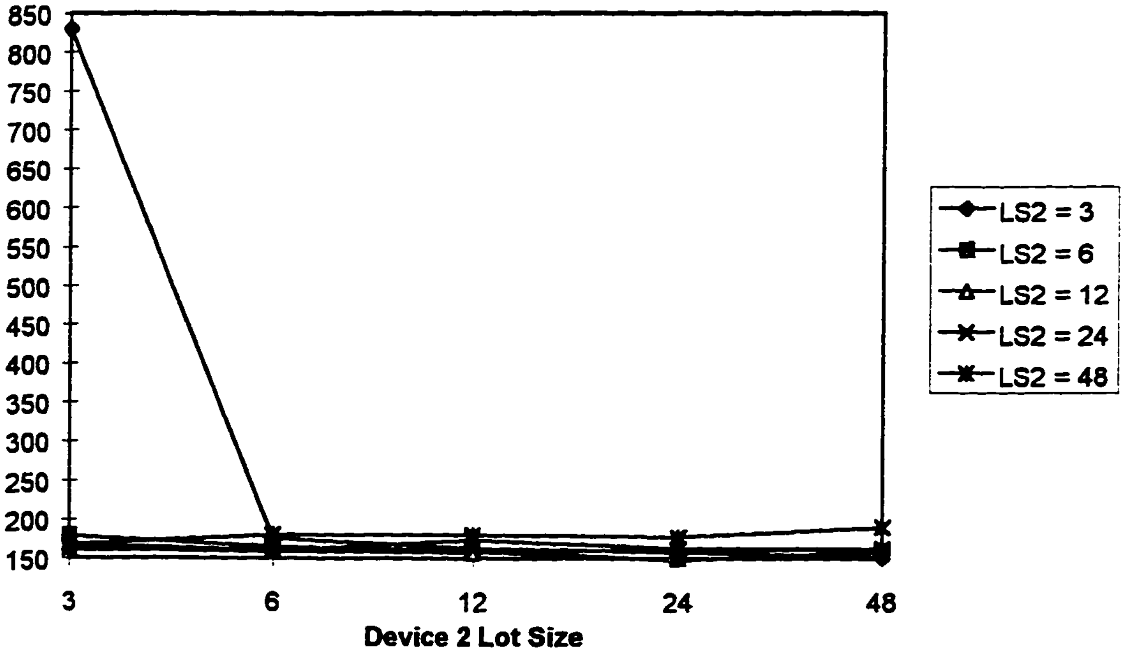


Figure 7-25: Production Costs 3-Way Interactions for Device 3, Holding Device 1 Lot Size = 24

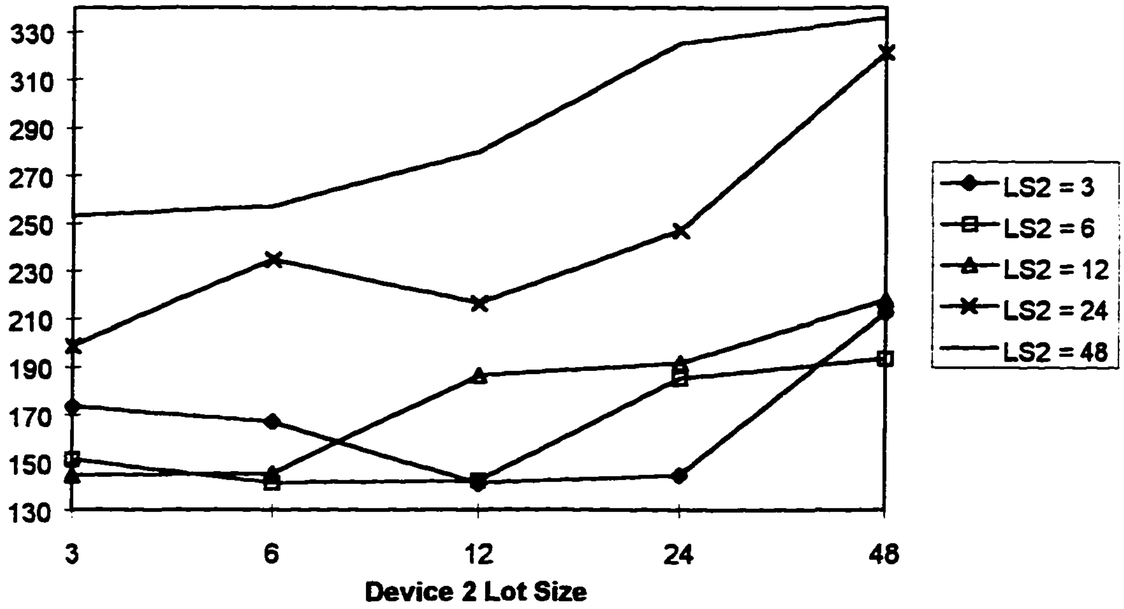


Figure 7-26: Production Costs 3-Way Interactions for Device 1, Holding Device 1 Lot Size = 48

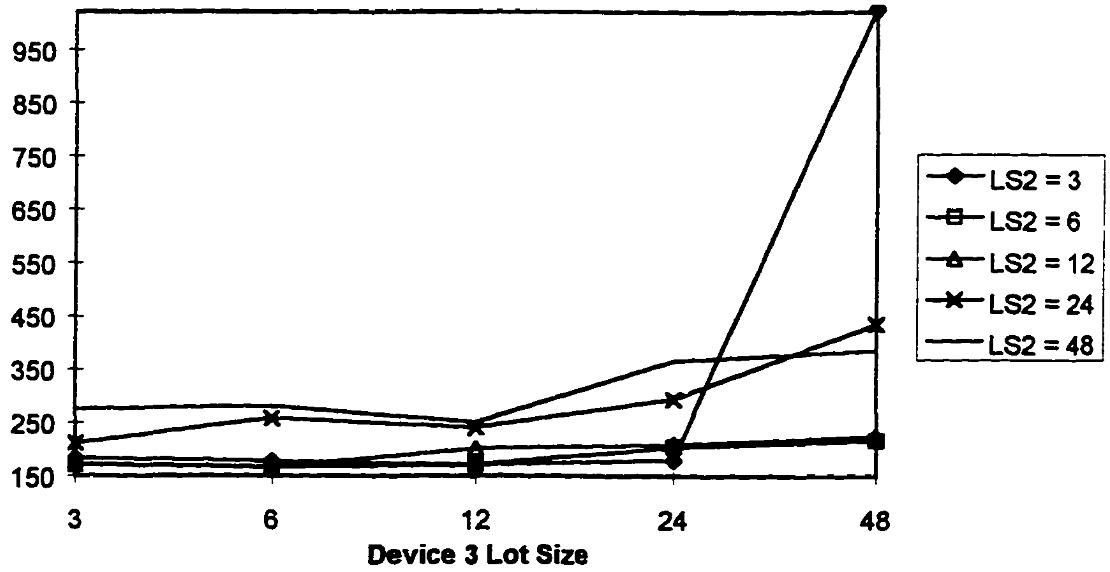


Figure 7-27: Production Costs 3-Way Interactions for Device 2, Holding Device 1 Lot Size = 48

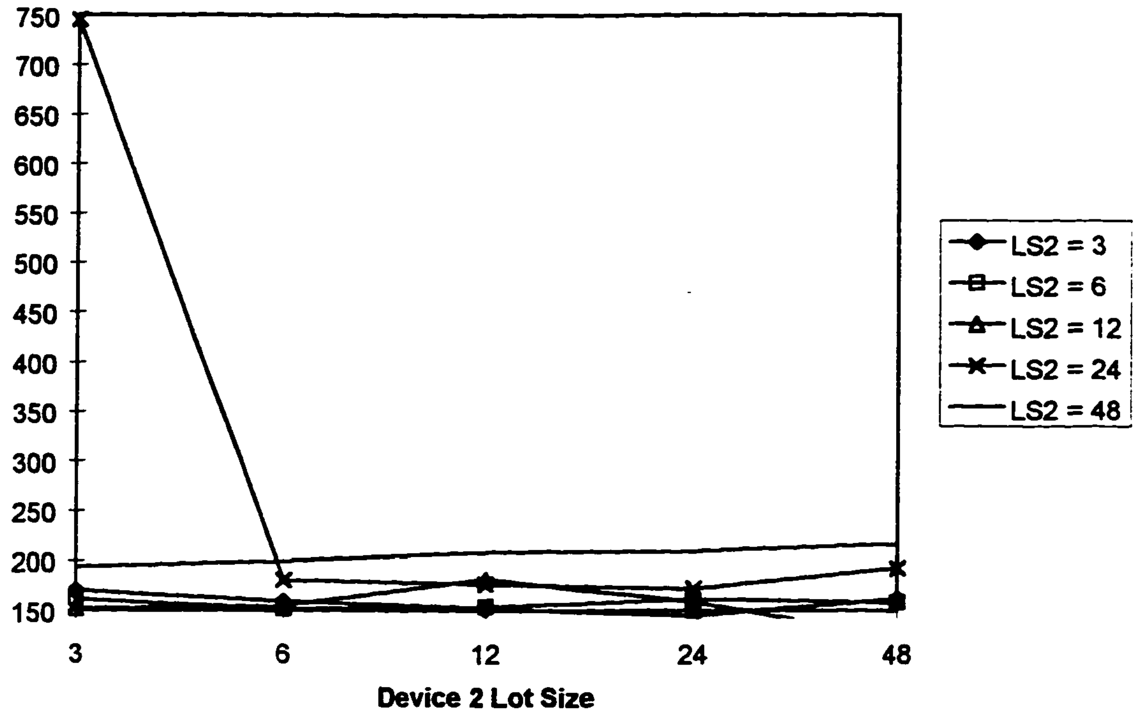


Figure 7-28: Production Costs 3-Way Interactions for Device 3, Holding Device 1 Lot Size = 48

Like the two-way interactions, the three-way interactions shown in Figures 7-14 through 7-28 have their most pronounced affects with the lot size combinations that tend to have large cycle times. In Figures 7-19, 7-22, 7-24,7-25, 7-27, and 7-28 there were at least one combination of lot sizes that produced very significant interactive affects. Again, these affects would be due to the lot sizes of the different devices that are in production, the load capacity of the of the processing equipment, the arrival rates of product to the individual work centers, and amount of shared resources between the different products.

Using regression analysis, significant operating parameters from the general linear model investigation were analyzed in an attempt to improve the analytical model shown in Eqn. 5-6. The results of this investigation are shown in Table 7-9 below.

Table 7-9: Regressions on Production Costs per Unit

Device	**Lot size**	**Adj. R-Sq**	**Prob>F**	**Indep. Variables**	**Prob > T**
1	3	0.9966	0.0001	Lot size Anal PC	0.0001 0.0001
1	6	0.9943	0.0001	Lot size Anal PC	0.0001 0.0001
1	12	0.9934	0.0001	Lot size Anal PC	0.0001 0.0001
1	24	0.9954	0.0001	Lot size Anal PC	0.0001 0.0001
1	48	0.9979	0.0001	Lot size Anal PC	0.0001 0.0001
2	3	0.4002	0.0001	Lot size Anal PC	0.0102 0.0001
2	6	0.9961	0.0001	Lot size Anal PC	0.0001 0.0001
2	12	0.9879	0.0001	Lot size Anal PC	0.0001 0.0001
2	24	0.6229	0.0001	Lot size Anal PC	0.0049 0.0001
2	48	0.3960	0.0001	Lot size Anal PC	0.0074 0.0001
3	3	0.4487	0.0001	Lot size Anal PC	0.0019 0.0001
3	6	0.9963	0.0001	Lot size Anal PC	0.0001 0.0001
3	12	0.9823	0.0001	Lot size Anal PC	0.0001 0.0001
3	24	0.5961	0.0001	Lot size Anal PC	0.0014 0.0001
3	48	0.9708	0.0001	Lot size Anal PC	0.0001 0.0001

Using the results of the regression model shown in Table 7-9, Eqn. 5-6 was modified as follows,

$$P = \sum_{j=1}^{k} \left[\frac{b_j T_j}{Y_j} \left(m_j + \sum_{i=1}^{n} \frac{C_{ij} + L_{ij}}{Q_j \eta_i} + D_j \right) - z_j Q_j \right] \qquad \text{Eqn. 7-1}$$

where b_j and z_j are scalar modifiers related to the processing activity, and D_j is the services and activity expenses other than direct processing that are directly related to the production process and are allocated on a per unit basis. It is believed that the two scalar modifiers suggested by the regression model and used in Eqn. 7-1 adjust the analytical production costs for load capacity utilization resulting from product arrival rates and interaction between lot sizes for the multiple devices. Further research would be required to confirm this theory.

Production costs were calculated using Eqn. 7-1, and a t-test was conducted using these new costs. Comparing the analytical production costs from Eqn. 7-1 and the simulation's production costs resulted in a failure to reject the null hypotheses. The results of this t-test are shown in Table 7-10 below.

Table 7-10: t-test of Production Costs Means

Results by Device					
Device	n	Means sim/anal	Std. Dev. sim/anal	Std. Err. sim/anal	Prob>|T|
1	95	164.759 163.930	10.848 1.298	1.1130 0.1332	0.4614
2	107	195.922 188.347	185.690 37.866	17.9514 3.6606	0.6800
3	106	172.866 170.627	145.206 35.849	14.1036 3.4819	0.8778

Results by Device by Lot Size						
Device	Lot size	n	Means sim/anal	Std. Dev. sim/anal	Std. Err. sim/anal	Prob>|T|
1	3	20	169.261 163.662	7.1208 0	1.592 0	0.0023
1	6	15	169.024 164.127	9.479 0	2.4476 0	0.0652
1	12	22	162.552 163.679	1.503 0	3.2056 0	0.7287
1	24	19	162.886 166.149	1.191 0	2.7334 0	0.2482
1	48	19	161.080 162.128	4.879 0	1.1194 0	0.3616
2	3	23	289.159 258.501	3.923 0	8.1817 0	0.7115
2	6	26	168.242 168.902	1.190 0	2.3337 0	0.7794
2	12	25	170.563 169.423	1.458 0	2.9176 0	0.6996
2	24	22	171.9331 179.979	1.384 0	2.952 0	0.0127
2	48	11	172.012 147.369	4.917 0	1.482 0	0.0001
3	3	20	267.131 242.234	3.214 0	7.1871 0	0.7328
3	6	24	159.187 160.458	1.281 0	2.6158 0	0.6314
3	12	24	154.903 154.050	9.639 0	1.9675 0	0.6686
3	24	20	150.164 162.596	9.801 0	2.1917 0	0.0001
3	48	18	135.539 135.646	3.245 0	7.6521 0	0.9890

In the results from Table 7-10, the analytical model's production costs per unit (Eqn. 7-1) were not found to be significantly different from the simulation's production costs per unit for all three of the device types produced at the 0.05 significance level. At the lot size level for each of the devices, the t-test again found there to be no significant difference between the analytical model and the simulation costs in eleven out of fifteen cases at the 0.05 significance level. From these results and from observation of the means, the analytical model is a good predictor of production costs.

7.1.3.2 Comparison of Overhead Costs. The following hypothesis is posed to investigate the similarity of overhead costs means between the simulation and the analytical model across the range of lot sizes investigated.

Hypothesis 6:

Ho_6: The overhead costs from the simulation model at various lot sizes are equal to the overhead costs generated by the analytical construct at the same lot sizes,

versus the alternative hypothesis of,

Ha_6: The overhead costs from the simulation model at various lot sizes are not equal to the overhead costs generated by the analytical construct at the same lot sizes.

Using regression analysis, and the analytical cycle time model, Q/Ψ, as the independent variable, the magnitudes of the variable β and the structural component variable θ were investigated for Eqn. 5-16. The results of this investigation are reported in Table 7-11.

Table 7-11: Regressions on Overhead Costs per Unit

Device	**Adj. R-Sq**	**Prob > F**	**Indep. Variables**	**Parameter Estimates**	**Prob > T**
1	0.9511	0.0001	intercept cycle time	1.16584 -0.48777	0.0001 0.0001
2	0.8705	0.0001	intercept cycle time	1.41904 -0.62478	0.0001 0.0001
3	0.8281	0.0001	intercept cycle time	1.17537 -0.29045	0.0001 0.0001

Using the parameter estimates from Table 7-11, overhead costs were generated with the analytical overhead cost model, Eqn. 5-16. A t-test of the analytical model's overhead costs and the simulation's overhead costs was performed. The results of the test are shown in Table 7-12 below.

From Table 7-12, the analytical model's overhead costs per unit were not found to be significantly different from the simulation's overhead costs per unit for all three of the device types produced at the 0.05 significance level. At the lot size level for each device, the t-test found that at the 0.05 significance level there were no significant differences between the analytical model and the simulation costs in eleven out of the fifteen lot size/device combinations. From these results and from observation of the means, the analytical model for overhead costs is a good predictor of actual overhead costs. As with the analytical model for production costs, the model for determining overhead costs could possibly be improved with the development of a cycle time variable that accounted for the interaction between devices and load capacity utilization.

7.1.3.3 Comparison of Setup Costs. The following hypothesis is posed to investigate the similarity of setup costs means between the simulation and the analytical model across the range of lot sizes investigated.

Hypothesis 7:

Ho_7: The setup costs from the simulation model at various lot sizes are equal to the setup costs generated by the analytical construct at the same lot sizes,

versus the alternative hypothesis of,

Ha_7: The setup costs from the simulation model at various lot sizes are not equal to the setup costs generated by the analytical construct at the same lot sizes.

The initial t-tests for hypothesis 7 resulted in a rejection of the null hypothesis. There were significant differences between the simulation's setup costs and the analytical model's setup costs. A regression analysis was performed on the simulated setup costs, using the analytical setup costs as the independent variable. The results of this regression analysis showed that the analytical model was a good predictor of setup cost but there was a need to scale the model's costs in most cases. Table 7-13 provides the results of this regression analysis.

After modifying Eqn. 5-25 as follows,

$$S_j = \sum_{j=1}^{k} \sum_{i=1}^{n} \frac{cS_{bj}}{\mathrm{T_j}} \left[\frac{{}_sS_{bj}}{\tau p_{bj}} \xi_j \tau s_{bj(1)} s_{bj}{}^{\left(\ln(r)/\ln(2)\right)} + \tau s_{bj} L_{ij} + C_{ij} \right] \qquad \text{Eqn. 7-2}$$

where, c is the scalar modifier suggested by the regression analysis, the analytical setup costs were recomputed and another t-test of hypothesis 7 was conducted. The result of this test is shown in Table 7-14.

Table 7-12: t-test of Overhead Costs Means

Results by Device

Device	n	Means sim/anal	Std. Dev. Sim/anal	Std. Err. Sim/anal	Prob>|T|
1	95	0.8162 0.8208	0.3578 0.3070	0.03671 0.03150	0.9233
2	107	1.1129 1.0892	0.4716 0.2898	0.04559 0.02802	0.6580
3	106	1.0023 0.9945	0.5061 0.1726	0.04916 0.01676	0.8804

Results by Device by Lot Size

Device	Lot size	n	Means sim/anal	Std. Dev. sim/anal	Std. Err. sim/anal	Prob>|T|
1	3	20	1.0914 1.1029	0.0865 0.0062	0.01934 0.0014	0.5592
1	6	15	1.0280 1.0468	0.10622 0.01446	0.02742 0.00373	0.5066
1	12	22	1.0076 0.9544	0.2043 0.0545	0.04357 0.01163	0.2498
1	24	19	0.7309 0.7160	0.18960 0.07063	0.04349 0.01620	0.7506
1	48	19	0.2228 0.2957	0.1474 0.1678	0.03382 0.03850	0.1641
2	3	23	1.2351 1.3461	0.6289 0.01346	0.13115 0.00280	0.4065
2	6	26	1.4098 1.2743	0.1752 0.0253	0.03436 0.00497	0.0006
2	12	25	1.2403 1.1321	0.2087 0.0514	0.04174 0.01029	0.0182
2	24	22	0.9217 0.8574	0.2179 0.1007	0.04646 0.02148	0.2189
2	48	11	0.2488 0.4804	0.0335 0.2996	0.01010 0.09033	0.0285
3	3	20	1.0326 1.1434	0.6130 0.0068	0.13708 0.00153	0.4293
3	6	24	1.2205 1.1149	0.1842 0.0155	0.03760 0.00317	0.0101
3	12	24	1.1450 1.0548	0.1697 0.0310	0.03464 0.00634	0.0170
3	24	20	0.9089 0.9157	0.1924 0.0490	0.04303 0.01096	0.8802
3	48	18	0.5913 0.6757	0.8659 0.1145	0.20410 0.02699	0.6867

Table 7-13: Regressions on Setup Costs per Unit

Device	Lot size	Adj. R-Sq	Prob>F	Indep. Variables	Parameter Estimates	Prob > |T|
1	3	0.2701	0.0001	setup model	0.559778	0.0001
1	6	0.9284	0.0001	setup model	1.452524	0.0001
1	12	0.2976	0.0001	setup model	0.702308	0.0001
1	24	0.9783	0.0001	setup model	1.475270	0.0001
1	48	0.4199	0.0001	setup model	1.511218	0.0001
2	3	0.2152	0.0001	setup model	0.389831	0.0001
2	6	0.6774	0.0001	setup model	0.778577	0.0001
2	12	0.8308	0.0001	setup model	1.063782	0.0001
2	24	0.8017	0.0001	setup model	0.983592	0.0001
2	48	0.2397	0.0001	setup model	0.655850	0.0001
3	3	0.2598	0.0001	setup model	0.706004	0.0001
3	6	0.4041	0.0001	setup model	0.971722	0.0001
3	12	0.7588	0.0001	setup model	1.329708	0.0001
3	24	0.4267	0.0001	setup model	1.030617	0.0001
3	48	0.4892	0.0001	setup model	1.759622	0.0001

In the t-test results shown in Table 7-14, the analytical model's setup costs were found to be not significantly different from the simulation's setup costs at the device type level. At the lot size level for each of the devices, the t-test again found there to be no significant difference between the analytical model and the simulation costs in six of the fifteen cases at the 0.05 significance level. There was a significant difference in the means of the other nine cases. Furthermore, in four of the six cases where the t-test failed to reject the null hypotheses, the variances about the means were so great that the value of these results is questionable. From these results, the analytical model can not be considered a good predictor of setup costs.

Table 7-14: t-test Results Comparison of Setup Costs Means

Results by Device

Device	n	Means sim/anal	Std. Dev. sim/anal	Std. Err. sim/anal	Prob>|T|
1	95	5193.2941 5458.3444	13690.027 13033.535	1404.567 1337.212	0.8914
2	108	4236.4634 5071.5879	12869.768 9908.343	1238.394 953.430	0.5937
3	106	5161.6312 4072.5832	12638.277 6733.648	1227.538 654.029	0.4348

Results by Device by Lot Size

Device	Lot size	n	Means sim/anal	Std. Dev. sim/anal	Std. Err. sim/anal	Prob>|T|
1	3	20	452.1804 1997.1792	93.044 462.189	20.805 103.348	0.0001
1	6	15	968.830 5172.650	34.735 1090.478	8.968 281.560	0.0001
1	12	22	1813.720 2655.543	471.518 1027.384	100.528 219.039	0.0015
1	24	19	13678.200 14609.803	28867.119 27710.859	6622.571 6357.307	0.9197
1	48	19	8947.327 3421.113	690.197 1038.397	158.342 238.224	0.0001
2	3	23	419.851 1773.417	49.597 390.036	10.341 81.328	0.0001
2	6	26	1596.021 5381.245	3710.302 9213.494	727.650 1806.914	0.0606
2	12	26	1666.869 4982.061	400.020 1000.889	78.450 196.290	0.0001
2	24	22	12170.044 10055.356	26797.426 18787.577	5713.230 4005.524	0.7635
2	48	11	8664.118 1479.917	762.777 220.833	229.985 66.583	0.0001
3	3	20	483.739 2300.733	58.701 367.847	13.126 82.253	0.0001
3	6	24	1870.849 5229.327	4232.967 10085.879	864.050 2058.771	0.1427
3	12	24	3796.088 4334.413	8303.726 6726.815	1694.991 1373.105	0.8062
3	24	20	12462.436 4508.198	25918.098 8177.543	5795.462 1828.554	0.2036
3	48	18	8455.715 3665.856	608.448 486.516	143.412 114.673	0.0001

7.1.3.4 Comparison of Net Profits. The following hypothesis is posed to investigate the similarity of net profit means between the simulation and the analytical model across the range of lot sizes investigated.

Hypothesis 8:

Ho_8: The net profits from the simulation model at various lot sizes are equal to the net profits generated by the analytical construct at the same lot sizes,

versus the alternative hypothesis of,

Ha_8: The net profits from the simulation model at various lot sizes are not equal to the net profits generated by the analytical construct at the same lot sizes.

In Chapter 5, a model for net profits was proposed (Eqn. 5-29). In the preceding sections of this chapter the various components of that model were tested for their ability to predict the costs associated with production, overhead, and performing setups. Due to the failure of the setup cost model to accurately predict the opportunity costs associated with setups, Eqn. 5-29 will be modified as follows:

$$\text{Max}\{\text{NP}\} = \text{Max}\left\{\sum_{j=1}^{k}\left(R_j - P_j - H_j\right)\right\}. \qquad \text{Eqn. 7-3}$$

To test this revised model's ability to predict net profits, hypothesis 8 was generated. A t-test of the net profits per device, and the net profits per device, by lot size, was conducted. The results of these t-tests are shown in Table 7-15.

In the t-test results shown in Table 7-15, the analytical model's net profits were found to be not significantly different from the simulation's net profits at the device type level. At the lot size level for each of the devices, the t-test again found there to be no significant difference between the analytical model and the simulation's net profits at the 0.05 significance level in thirteen of the fifteen cases. From these results we must fail to reject the null hypothesis, and conclude that the analytical model, Eqn. 7-3, does provide a reasonable prediction of the firm's net profits.

Table 7-15: t-test of Net Profit Means

Results by Device

Device	n	Means sim/anal	Std. Dev. Sim/anal	Std. Err. Sim/anal	Prob>|T|
1	290	68397137 68249198	32108988 32582282	1885504 1913297	0.9561
2	290	58432575 55532504	40419675 41705401	2373525 2449025	0.3955
3	290	76665320 73889172	25475812 27628029	1495991 1622373	0.2089

Results by Device by Lot Size

Device	Lot size	n	Means sim/anal	Std. Dev. sim/anal	Std. Err. sim/anal	Prob>|T|
1	3	60	52612240 53463572	26443573 26344047	3413850 3401001	0.8601
1	6	55	76464911 77145656	17478747 17370929	2356833 2342295	0.8381
1	12	59	82268016 82973644	21578836 21928045	2809325 2854788	0.8605
1	24	61	73240890 72772426	25323943 26006946	3242398 3329848	0.9199
1	48	55	57297418 54670526	50300411 50815916	6782506 6852016	0.7858
2	3	56	57140947 37741629	37400914 39148899	4997907 5231491	0.0085
2	6	58	72729639 74695838	25470773 25561605	3344476 3356403	0.6789
2	12	61	76194418 78109502	23494287 23970161	3008135 3069064	0.6567
2	24	60	59828015 59292204	37299071 38476765	4815289 4967329	0.9384
2	48	55	23448988 24296807	51714291 49941122	6973153 6734059	0.9305
3	3	56	66516581 50759632	34035849 35119642	4548231 4693059	0.0176
3	6	57	80188260 81751586	24525457 24447224	3248476 3238113	0.7339
3	12	60	81678538 83830800	23183474 23042163	2992973 2974730	0.6110
3	24	57	81261104 80006391	22396029 22422071	2966426 2969875	0.7656
3	48	60	73411469 72254464	18661110 17517584	2409139 2261510	0.7269

7.2 Comments About the Lot Size - Material Release Relationship

From the two hundred and ninety simulation runs that were conducted, it was seen that both the lot size and the material release rate schedule had significant effects on the operating expenses and net profits of the production system being investigated. Some of the effects due to changes in lot sizes and the material release schedule, are listed below:

1. there were significant changes in throughput;
   a. with the material release schedule held at 96 units per shift, and varying lot size:
      i. minimum system output = 163440 units
      ii. maximum system output = 211194 units
   b. with the material release schedule held at 144 units per shift, and varying lot size:
      i. minimum system output = 91035 units
      ii. maximum system output = 308946 units
   c. across all material release schedules and lot sizes:
      i. minimum system output = 91035 units
      ii. maximum system output = 324768 units
2. there were significant changes in work-in-process;

    - a. with the material release schedule held at 96 units per shift, and varying lot size:
        - i. minimum work-in-process = 7350 units
        - ii. maximum work-in-process = 101680 units
    - b. with the material release schedule held at 144 units per shift, and varying lot size:
        - i. minimum work-in-process = 36754 units
        - ii. maximum work-in-process = 427428 units
    - c. across all material release schedules and lot sizes:
        - i. minimum work-in-process = 7350 units
        - ii. maximum work-in-process = 552048 units

3. there were significant changes in cycle time;
    - a. with the material release schedule held at 96 units per shift, and varying lot size:
        - i. minimum cycle time = 0.0349 years
        - ii. maximum cycle time = 0.6221 years
    - b. with the material release schedule held at 144 units per shift, and varying lot size:
        - i. minimum cycle time = 0.1189 years
        - ii. maximum cycle time = 4.1075 years
    - c. across all material release schedules and lot sizes:
        - i. minimum cycle time = 0.0349 years

ii. maximum cycle time = 5.3790 years

4. the location of the bottleneck for each device moved.

From these observations, it can be seen that not only will lot size affect cycle time, work-in-process, and throughput, but the material release rate will also affect them. Referencing Appendix C, it can be seen that at lower material release rates, the overall effect of changes in lot size are not as dramatic as compared to the higher material release rates. The implications of this observation is that when operating at or near the systems capacity, the choice of both lot size and the material release rate for each product being produced will have vary significant effects upon the performance and net profits of the production system. When operating at levels well below the production systems capacity, the impact of lot size and/or the rate of material release become less significant.

7.3 Summary

In Chapter 6, a simulation model was described as the primary vehicle of validation for the analytical models developed in Chapter 5. It was determined that two hundred and ninety simulation runs, using different combinations of lot sizes between the three devices, would be necessary in order to fully investigate the effects of lot size and the material release schedule (MRS) on net profits and the various categories of operating expenses.

The investigation, and subsequent testing of the production data from Texas Instruments' Lubbock plant revealed that there were significant differences in operating expenses as a result of their change in the standard production lot size. The data from the simulation runs also showed that changes in lot size, as well as in the material release rate, had significant effects upon work-in-process, throughput, and cycle time. Statistical analysis of these simulation runs showed that the interactions between the lot sizes of the multiple products, and the interactions between the material release rates of the multiple products, also significantly affected costs, work-in-process, throughput, and cycle time. Tables 7-8 and 8-1 show the results of two of these statistical analyses.

Several regression analysis were performed upon the production data, reference Tables 7-2, 7-3, and 7-4. From these analyses it was found that cycle time was a very significant factor in the prediction of virtually every category of operating expense. Figure 7-1 illustrates the curvilinear relationship between cycle time and operating expenses. As cycle time increases, there was a corresponding increase in operating expenses, up to the point where the work-in-process level starts to choke-off the flow of materials through the system. At that point, there is less production activity, and as a result, operating expenses start to decrease as cycle time increases.

In both of the production costs and the overhead costs, the magnitude of these respective operating expenses can vary from one firm to the next, depending upon how each firm collects and allocates their operating expenses. The interpretation and allocation of the costs used in this study are not necessarily the same as Texas Instruments' interpretation and allocation of them in their usage of the models developed by this thesis. Of the three components of the analytical model for net profits that were tested, the models for production costs and for overhead costs were determined to be good predictors of their respective operating expenses. The model for setup costs failed to make good predictions of the setup costs. Possible reasons for this failure are: (1) the degree of interaction between devices and lot sizes, and (2) the difference in operations at the various work centers.

Based on the tests of the model components presented here, the analytical model for net profits was modified and tested. The model showed that it did provide good estimates of the firm's net profits. Chapter 8 shall discuss the contributions and the limitations of this research.

CHAPTER 8

CONTRIBUTIONS, LIMITATIONS, AND FUTURE RESEARCH

8.1. Contributions of the Research

As products and markets mature, product offerings proliferate, giving rise to substantial change in production processes. These changes tend to increase the usage of job shops. Literature has shown the impact that lot size can have on the efficiency of the job shop process flow. This research has extended that knowledge to show how the interactions between the lot sizes of multiple products can affect not only throughput and work-in-process, but cycle times, operating expenses, bottleneck locations, and net profits.

In the literature, many authors have shown, or alluded, that by reducing lot sizes, throughput and cycle times will be improved. Table 8-1 shows how lot size affected the three products utilized in the simulation. From this table, it can be seen that the assertions made in the literature are true up to a point. At all four material release rates, using a standard lot size for all three products, reductions in lot size did result in improvements in both throughput and cycle times, except at the lot size of three units per lot. Although, using mixed lot sizes gave the best results in three of the four cases. At the material release rate of ninety-six units per shift, the standard lot size of twenty four units had the best net profits ($248,257,432.00), while the mixed lot size run of forty-eight, six, and three had comparable net profits ($244,156,864.00), as well as the best output, work-in-process inventory level, and cycle time. Reference Appendix C for the full summary of simulation results.

One explanation for the effects shown in Table 8-1 is that in a single-product production system, reductions in lot size will improve the efficiency of the system. This causes the product to flow through the production system more smoothly (i.e., increases the arrival rate of the product to each operation in the production system). Up to a point, this increased arrival rate results in an increased throughput and a decreased cycle time. Reduced lot sizes results in increases in the arrival rates of jobs. If service rates are invariant with respect to lot size, then more processing time is needed to accommodate the increases in the number of jobs. More jobs will also mean more setups. In the simulation, both setups and operation times are moderated by the simulations model's ability to batch jobs.

Table 8-1: Summary of Simulation Results

Device Summary						Plant Summary		
Run	Dev	Lot size	Rel/ shift	Net Profit	Operating Expenses	Total Output	Total WIP	Combined Cycle time
42	1	12	138	115132508	34391679	298488	15720	0.053 years
	2	24	132	106661937	35020064			
	3	12	138	113972052	34990168			
38	1	12	138	106138210	34104813	286284	43092	0.151 years
	2	12	138	96299764	39930815			
	3	12	138	104516487	34914225			
1	1	3	142	-8664133	32196997	96066	357330	3.719 years
	2	3	142	-22210997	35008483			
	3	3	142	-12380394	36391819			
82	1	6	189	67816630	50086846	324768	257274	0.792 years
	2	6	189	80993948	64673745			
	3	6	189	90340899	56276142			
119	1	24	180	45034278	42115804	237840	325632	1.369 years
	2	24	180	11809233	49290863			
	3	24	180	78872237	43056399			
75	1	48	168	-47097632	31754905	96192	552048	5.739 years
	2	48	168	-70836236	37265971			
	3	48	168	35167167	33354923			
195	1	48	144	120353193	27103740	308946	36854	0.118 years
	2	6	144	104562848	44536631			
	3	6	144	115852725	38574781			
210	1	12	144	95928552	35425271	276408	85212	0.308 years
	2	12	144	83660355	41693527			
	3	12	144	92472783	36194084			
205	1	48	144	-23570823	25202982	104016	427248	4.107 years
	2	48	144	-47265622	29651462			
	3	48	144	46967169	26359255			
254	1	24	96	84547792	19495025	210552	9568	0.045 years
	2	24	96	80086410	22932159			
	3	24	96	83623230	20120199			
282	1	48	96	91282892	13404264	211194	9000	0.043 years
	2	6	96	74457497	28611154			
	3	3	96	78416475	25716279			
217	1	6	95	79780747	24358721	210468	7350	0.035 years
	2	6	96	74381157	28631651			
	3	6	96	79152777	24870465			
261	1	3	96	78778518	25267878	210399	8898	0.042 years
	2	3	96	73181099	29711378			
	3	3	96	78003836	25784962			
234	1	48	96	90677412	13132827	168021	91056	0.542 years
	2	48	96	80048962	22973153			
	3	3	96	79328284	24854085			

NOTE: 1 REL denotes the specific material release rate for the j^{th} product.

2 Tput mean total system output in units.

From queuing theory, we know that when product arrival rates approach an operation's service rate that large queues will form. Thus, when the lot size of a product becomes too small, the system starts to choke. This explanation is supported by Campbell, Dudek, and Smith (1970), Spence and Porteus (1987), and Potts and Baker (1989), reference the discussion in section 2.4.4.

The smoothing effects of reduced lot sizes, as discussed above, also applies in the multiple product case as can be seen in Appendix A and Table 8-1. The primary difference between the single product case and the multiple product case is the interaction of the product lot sizes. Note in Table 8-1, runs 205, and 210, where the reduction in the standard lot size from 48 units per lot to 24 units per lot resulted in significant improvements in throughput and cycle times. Now note in Table 8-1, run 195, the mixed lot sizes of 48, 6, and 6 units per lot for products 1, 2, and 3, respectively, resulted in not only higher throughput and lower cycle time, but also resulted in higher net profits.

As stated by Goldratt and Cox (1992) and Goldratt and Fox (1986), the goal of the firm is to make a profit both in the present and in the future. As shown in Table 8-1, the interaction of lot sizes between multiple products being produced in the same job shop can have significant impacts upon not only the firm's ability to meet its competitive objectives, but also its ability to make a profit. By taking a profit orientation, the models developed in this research provide the job shop operations manager a tool for maximizing the efficiency and net profits of his operation.

Dependent upon the firm's competitive strategies and objectives, the results of applying the knowledge developed by this research can make one or more of the following contributions:

1. maximize net profits while simultaneously decreasing work-in-process across one or more products,
2. maximize net profits while simultaneously increasing throughput across one or more products,
3. maximize net profits while simultaneously decreasing cycle times across one or more products, or
4. contingent upon further research, maintain or move the bottleneck for one or more products to a desired operation.

In the typical job shop operation, there will already be work in the production stream. Furthermore, it is not usual for new jobs to be introduced into this existing process stream of work. The contribution that this research can make in this scenario is to give the operations manager the ability to appropriately size the new job's lots and determine the appropriate material release schedule for the new job, given the lot sizes and material release schedules of the work currently in the system, such that one or more of the above contributions will occur. With the modeling tools developed here, it is even possible to adjust the lot sizes of all existing products so as to accommodate the new product.

Among the most important contributions of this research are the methodology and the models created by the research. The rough-cut methodology developed in this research is to:

1. gather specific data items over a period of time (the more periods the better);
2. use this data to,
    a. parameterize the analytical models, and
    b. drive the simulation model;
3. statistically compare the results of the analytical and simulation models, and adjust as necessary to verify and validate their correctness; and
4. use the models to determine lot-sizing strategies consistent with the profit-maximizing and critical success factors of interest to the firm. These

critical success factors might include one or more of the following;

a. cycle time,
b. work-in-process,
c. throughput, and/or
d. bottleneck maintenance.

The analytical models developed in this research are general and applicable to all discrete manufacturing processes per se, taking a profit-centric, bottleneck-focused approach. The simulation model developed, while specific to Texas Instruments, is easily generalizeable to other discrete, multiple product, multiple operations, manufacturing contexts. All that is necessary to accomplish the generalizing of the simulation model is to modify the process specification table for the process of interest, and provide a product routing table for each product to be included. Specific changes to the code would have to be made on a case-by-case basis. Possible changes to the code would include: additions to the number of resource types, and specific operational logic for special case activities.

8.2. Limitations of the Research

There are four limitations currently identified with this research. It is believed that, as cycle times are reduced, the demand for a firm's product will increase. The first limitation of the model developed by this research is the absence of empirical data for formulating relationships between product price and demand as functions of cycle time. Even though there are some theories and models available in the economic literature, the business environment has so many confounding elements that it is questionable how to parameterize these models in order to predict future prices. It is sufficient to say that cycle time will have a significant effect upon the demand and will allow the manufacturer to adjust his prices.

A second limitation of the model developed by this research is that only one division of one company was investigated. It is possible that the effects seen in this research characterize this operation only. To eliminate this concern, the study should be expanded to include more companies both within and outside of the semiconductor industry. By the inclusion of more companies, the general applicability of the models developed by this research and its findings will increase.

The third limitation of the model developed by this research is the ability to accurately predict cycle times as a function of lot size. As was seen in Chapter 7, cycle time is a significant variable in the determination of operating expenses. Even though this limitation can be circumvented to some degree by simulation and/or other predictor variables, the knowledge of what a product's cycle time will be for a given lot size and material release schedule is an important decision variable for an operations manager. From observations of the data generated by the simulation runs, cycle time is affected by many variables.

Contrary to the implications of current literature, it cannot be generally assumed that by reducing a product's lot size that cycle time will be reduced also. In the single product case, running near capacity, lot sizes that are odd multiples of the bottleneck's capacity will cause spikes (increases) in cycle time. In the multi-product case, not only is there the same odd lot size problem to be dealt with, but, there is an interaction problem between the lot sizes of products that share resources. There is also an interaction problem between lot size and the rate at which material is released in to the system. How a given product's lot size and its material release rate interact with the other products being produced must be considered. Table 8-2 shows the result of a variance analysis on cycle time with respect to operational parameters that can affect cycle time.

TABLE 8-2: Significant Parameters to Cycle Time.

```
Dependent Variable: CYCLE1
Source            DF     Sum of Squares     Mean Square     F Value      Pr > F
Model             169      1400.5850682       8.2874856       77.63      0.0001
Error             700        74.7274017       0.1067534
Corrected Total   869      1475.3124698
R-Square 0.9493   C.V. 38.7999    Root MSE 0.32673    CYCLE1 Mean 0.84209
Source            DF       Type III SS      Mean Square      F Value      Pr > F
LS1                4       34.16104445       8.54026111        80.00      0.0001
LS2                4       20.17283438       5.04320859        47.24      0.0001
LS3                4        1.18122057       0.29530514         2.77      0.0266
LS1*LS2           16      159.53974883       9.97123430        93.40      0.0001
LS1*LS3           16       66.46847443       4.15427965        38.91      0.0001
LS2*LS3           16       40.33690803       2.52105675        23.62      0.0001
LS1*LS2*LS3       64       65.38569781       1.02165153         9.57      0.0001
REL1               8       35.40195569       4.42524446        41.45      0.0001
REL2               8       16.41797321       2.05224665        19.22      0.0001
REL3               8        6.80741810       0.85092726         7.97      0.0001
LS1*REL1           4        6.54339303       1.63584826        15.32      0.0001
LS2*REL2           6        2.70479571       0.45079929         4.22      0.0003
LS3*REL3           6        6.90051214       1.15008536        10.77      0.0001
Dependent Variable: CYCLE2
Source            DF     Sum of Squares     Mean Square     F Value      Pr > F
Model             169      5242.0594648      31.0181033      106.39      0.0001
Error             700       204.0881508       0.2915545
Corrected Total   869      5446.1476156
R-Square 0.9625    C.V. 43.4724     Root MSE 0.53995    CYCLE2 Mean1.24207
Source            DF       Type III SS      Mean Square      F Value      Pr > F
LS1                4       55.15374186      13.78843547        47.29      0.0001
LS2                4      161.44214032      40.36053508       138.43      0.0001
LS3                4        9.09177271       2.27294318         7.80      0.0001
LS1*LS2           16      465.17219786      29.07326237        99.72      0.0001
LS1*LS3           16      111.31402983       6.95712686        23.86      0.0001
LS2*LS3           16      269.73279405      16.85829963        57.82      0.0001
LS1*LS2*LS3       64      228.18623132       3.56540986        12.23      0.0001
REL1               8       32.74544987       4.09318123        14.04      0.0001
REL2               8      280.24103084      35.03012886       120.15      0.0001
REL3               8        7.76828275       0.97103534         3.33      0.0009
LS1*REL1           4        6.73104730       1.68276183         5.77      0.0001
LS2*REL2           6       28.45320876       4.74220146        16.27      0.0001
LS3*REL3           6        9.41188276       1.56864713         5.38      0.0001
Dependent Variable: CYCLE3
Source             DF    Sum of Squares     Mean Square      F Value      Pr > F
Model             169      386.03357122      2.28422231        63.33      0.0001
Error             700       25.24618204      0.03606597
Corrected Total   869      411.27975326
R-Square 0.9386   C.V. 34.06357    Root MSE 0.18991    CYCLE3 Mean 0.55751
Source            DF       Type III SS      Mean Square      F Value      Pr > F
LS1                4        7.10141542       1.77535386        49.23      0.0001
LS2                4        7.86425373       1.96606343        54.51      0.0001
LS3                4        1.14918132       0.28729533         7.97      0.0001
LS1*LS2           16       26.17600359       1.63600022        45.36      0.0001
LS1*LS3           16       12.99117429       0.81194839        22.51      0.0001
LS2*LS3           16       13.87258875       0.86703680        24.04      0.0001
```

TABLE 8-2: continued.

LS1*LS2*LS3	64	16.96932987	0.26514578	7.35	0.0001
Source	DF	Type III SS	Mean Square	F Value	Pr > F
REL1	8	8.40933176	1.05116647	29.15	0.0001
REL2	8	6.16618656	0.77077332	21.37	0.0001
REL3	8	5.26602033	0.65825254	18.25	0.0001
LS1*REL1	4	3.31128786	0.82782197	22.95	0.0001
LS2*REL2	6	7.01318360	1.16886393	32.41	0.0001
LS3*REL3	6	3.13580682	0.52263447	14.49	0.0001

NOTES: 1 LS# means lot size for the j^{th} product.
2 REL# means material release rate for the j^{th} product.
3 * indicates the interaction between two or more items.

As discussed in the previous paragraph, Table 8-2 shows that there are significant interactions between the lot sizes of the three products used in the simulation. There are also significant interactions between the lot size of a product and the rate at which new material is released into the production system for that product. From Appendix C, it can be seen that these interactions are more prominent when the system in near its maximum capacity level, or above. It can also be seen that at lower capacity levels, if the wrong mix of lot sizes are chosen, there can still be significant negative results.

The fourth limitation of the model developed by this research is the complexity of the analytical models themselves. The models developed by this research are intended to improve current operating practices in the semiconductor industry. The complexity of these models may deter many operations managers from actual use. This problem may be nullified through the incorporation of these analytical models into a decision support system.

8.3. Future Research

Limitations of this research suggest the following topics for future research:

1. Extend the data base for this research to include more companies both inside and outside of the semiconductor industry.
2. Develop a model for the identification and management of the floating bottleneck problem.
3. Develop a model of product demand with respect to improvements in manufacturing cycle times.
4. Develop a model for the prediction of cycle time based upon the operational parameters shown in Table 8-1.

Other areas of future research related to this research are:

5. How does the cross training of production operators affect the production system?
   a. Two cases could be investigated with respect to operator cross training:
      i. Operator absenteeism, and

ii. Reduction of force.

6. How do changes in the queuing discipline (i.e., FIFO, LIFO, SPT, etc.) change the results of this study?
7. Should a model be developed for the identification and management of the floating bottleneck problem associated with changes in product lot sizes and material release rates, how would the application of a synchronous manufacturing system affect the findings of this study?
8. How would a group technology architecture affect the performance variables of interest?
9. How does lot size affect the arrival rates of product to each operation in an n job, m machine job shop?

8.4. Summary

In Chapter 1, a problem was identified. The problem is that a profit maximizing model for the determination of an optimal lot size for the n job, m machine, job shop has yet to be developed. Chapter 2 reviewed the relevant literature on this subject. From this review, a theoretical foundation was formulated for the development of an analytical model to resolve the identified problem.

Because the model developed by this research focused upon the batch-type processing typically found in the semiconductor industry, Chapter 3 provides a background for the unique processing that characterizes the fabrication of integrated circuits. Chapter 4 reviews several research methodologies, and synthesizes them into a methodology for the conduct of this research. Chapter 5 explains the situation identified in the problem statement through the development of an analytical model. Chapter 6 described the production data that were collected from Texas Instruments' Lubbock Plant. Chapter 6 also described the simulation model that was utilized in researching the effects of lot size changes. Chapter 7 discussed the statistical analysis of both the data collected from Texas Instruments and the data generated by the simulation model. Chapter 8 discussed the contributions and limitations of this research.

This dissertation has shown the effect of lot size on the firm's net profits. This dissertation has also shown the magnitude of the affect on the multiple product, multiple operation production system cause by the interaction between the lot sizes of multiple products. With the selection of the best combination of lot sizes, throughput can be increased, and both work-in-process and cycle time can be reduced. Furthermore, with the selection of the optimal combination of lot sizes, net profits can be maximized. With the wrong combination of lot sizes, especially at higher material release rates, the production system can become clogged with work-in-process and throughput will be diminished. The analytical models of production costs and overhead costs were shown (reference Chapter 7) to be good predictors of their related operating expenses, and, through their usage, appropriate lot sizes can be selected for maximizing expected net profits.

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APPENDIX A

Summary of Simulation Runs

Table A-1: continued.

DEVICE LEVEL STATISTICS							FACTORY LEVEL STATISTICS			
OBS	RUN	DEV	LS	REL RATE	NET PROFIT	OPERATING EXPENSE	BNK WC	TOTAL TPUT	TOTAL WIP	CYCLE TIME
1	1	1	3	142	-8664133.91	32196997.90	2	96066	357330	3.71963
2	1	2	3	142	-22210997.68	35008483.95	2			
3	1	3	3	142	-12380394.57	36391819.80	2			
4	2	1	3	142	40506679.91	37091232.19	43	183726	254796	1.38683
5	2	2	3	142	21606287.02	43435172.90	43			
6	2	3	6	141	28118550.45	36761089.81	43			
7	3	1	3	142	51925169.50	37618977.36	43	195903	232224	1.18540
8	3	2	3	142	33605941.39	43952713.54	43			
9	3	3	12	138	28499225.54	34422831.67	43			
10	4	1	3	142	44885443.83	37531384.80	43	192405	244809	1.27236
11	4	2	6	141	21499699.83	42706450.77	43			
12	4	3	3	142	37296508.90	38319425.47	43			
13	5	1	3	142	52168424.07	37610218.11	43	207624	209403	1.00857
14	5	2	6	141	36012844.05	42264491.56	43			
15	5	3	6	141	47059621.82	36859368.66	43			
16	6	1	3	142	51882305.92	37546713.50	55	251403	98625	0.39230
17	6	2	6	141	107460802.88	43188122.26	2			
18	6	3	48	120	85552128.82	20033671.58	2			
19	7	1	3	142	53396415.21	37612407.92	43	201597	223434	1.10832
20	7	2	12	138	23023824.15	39989743.03	43			
21	7	3	3	142	47972460.61	38368006.50	43			
22	8	1	3	142	51940727.52	37574086.18	55	244968	122265	0.49911
23	8	2	12	138	85154450.89	40058919.25	43			
24	8	3	24	132	84335819.91	29779819.55	43			
25	9	1	3	142	51538273.90	37521530.64	55	248739	169710	0.68228
26	9	2	12	138	107165743.65	40174212.96	2			
27	9	3	48	120	54739307.89	33246034.79	2			
28	10	1	3	142	51340976.77	37530289.90	55	246342	122829	0.49861
29	10	2	24	132	77317265.48	34681869.58	43			
30	10	3	12	138	95221039.49	35128652.52	43			
31	11	1	3	142	51876577.01	37546713.50	55	258112	90399	0.35023
32	11	2	24	132	100018718.51	34774104.55	43			
33	11	3	24	132	105632190.20	30015837.70	43			
34	12	1	3	142	51448570.51	37482661.44	55	244710	98712	0.40338
35	12	2	24	132	106777145.27	34692117.91	2			
36	12	3	48	120	85365593.50	19988999.37	32			
37	13	1	3	142	56134621.03	37637043.33	55	248943	104604	0.42019
38	13	2	48	120	75154600.52	23440974.58	40			
39	13	3	6	141	110775821.69	37354113.34	40			
40	14	1	3	142	57627653.00	37627189.17	55	241086	114240	0.47386
41	14	2	48	120	65762720.92	23143773.02	40			
42	14	3	12	138	107508544.14	34811479.86	40			
43	15	1	3	142	60553218.22	37568064.19	55	228936	133776	0.58434
44	15	2	48	120	50258889.49	23635692.84	40			
45	15	3	24	132	101987133.14	30195271.06	40			
46	16	1	6	141	33292900.03	35446844.54	43	178176	258285	1.44961
47	16	2	3	142	19272962.81	42931723.71	43			
48	16	3	3	142	30364027.68	37460602.32	43			
49	17	1	6	141	50452272.25	36400508.53	43	206748	215211	1.04093
50	17	2	3	142	37667083.17	44161523.25	43			
51	17	3	6	141	43475131.43	37194410.21	43			

Table A-1: continued.

DEVICE LEVEL STATISTICS							FACTORY LEVEL STATISTICS			
OBS	RUN	DEV	LS	REL RATE	NET PROFIT	OPERATING EXPENSE	BNK WC	TOTAL TPUT	TOTAL WIP	CYCLE TIME
52	18	1	6	141	93405062.55	36614015.40	55	272784	60651	0.22234
53	18	2	3	142	107479840.16	44953206.71	2			
54	18	3	48	120	84828170.84	20337442.58	2			
55	19	1	6	141	52565164.82	36443209.91	43	209778	208257	0.99275
56	19	2	6	141	34694305.31	42569379.36	43			
57	19	3	3	142	50726739.56	38372473.72	43			
58	20	1	6	141	92180876.44	36541751.54	43	259410	94314	0.36357
59	20	2	6	141	81677367.34	42588594.98	43			
60	20	3	24	132	74642017.33	29641335.71	43			
61	21	1	6	141	93226115.00	36456348.79	55	271236	57354	0.21145
62	21	2	6	141	107894366.60	43167625.60	2			
63	21	3	48	120	85473556.11	20024737.14	32			
64	22	1	6	141	92553382.47	36607445.96	43	269994	79590	0.29478
65	22	2	12	138	82806467.75	39966684.29	43			
66	22	3	12	138	91042357.80	34740004.33	43			
67	23	1	6	141	92960770.81	36522043.21	55	280398	53946	0.19239
68	23	2	12	138	100248346.48	40458604.10	43			
69	23	3	24	132	102579801.07	30137197.19	43			
70	24	1	6	141	93479448.34	36542846.44	55	269478	57432	0.21312
71	24	2	12	138	107814304.82	40353558.73	2			
72	24	3	48	120	85350937.64	20069409.34	32			
73	25	1	6	141	92106128.39	36570219.12	43	262272	91896	0.35038
74	25	2	24	132	68458403.47	34379543.86	43			
75	25	3	6	141	94044715.24	37384267.08	43			
76	26	1	6	141	93277613.78	36505619.60	55	281748	49716	0.17646
77	26	2	24	132	98187225.32	34722862.90	43			
78	26	3	12	138	108426685.51	34869553.73	43			
79	27	1	6	141	93894153.30	36618395.03	55	284160	37542	0.13212
80	27	2	24	132	105698639.50	34768980.38	2			
81	27	3	24	132	111328102.09	29985311.69	2			
82	28	1	6	141	99075379.22	36622774.65	40	270120	63915	0.23662
83	28	2	48	120	74694738.26	23430726.25	40			
84	28	3	3	142	111572194.13	38707515.26	40			
85	29	1	6	141	99344252.51	36653432.05	40	267666	64086	0.23943
86	29	2	48	120	73311167.29	22979799.75	40			
87	29	3	6	141	110837054.69	37347412.51	40			
88	30	1	6	141	97580999.04	36658906.58	40	259326	78528	0.30282
89	30	2	48	120	63493425.31	23205263.00	40			
90	30	3	12	138	108265876.09	35048242.55	40			
91	31	1	12	138	35660153.49	33892401.91	43	194322	235269	1.21072
92	31	2	3	142	32067699.36	43911720.22	43			
93	31	3	3	142	43202401.86	38237898.70	43			
94	32	1	12	138	73971920.27	33947147.26	43	234735	141621	0.60332
95	32	2	3	142	70414816.80	44157680.13	43			
96	32	3	24	132	55306302.08	29699409.58	43			
97	33	1	12	138	114809424.01	34411387.83	2	281370	40056	0.14236
98	33	2	3	142	107960340.70	44779625.63	2			
99	33	3	48	120	84308383.93	20417852.55	2			
100	34	1	12	138	89850005.01	34139850.89	43	267336	86180	0.32237
101	34	2	6	141	82723691.45	42910563.34	43			
102	34	3	12	138	86734411.93	34927627.60	43			

Table A-1: continued.

DEVICE LEVEL STATISTICS							FACTORY LEVEL STATISTICS			
OBS	RUN	DEV	LS	REL RATE	NET PROFIT	OPERATING EXPENSE	BNK WC	TOTAL TPUT	TOTAL WIP	CYCLE TIME
103	35	1	12	138	102233446.07	34155179.59	43	277500	59058	0.21282
104	35	2	6	141	95579071.55	43086920.01	43			
105	35	3	24	132	92390671.89	30132729.97	43			
106	36	1	12	138	114980229.51	34240582.34	2	280002	37446	0.13373
107	36	2	6	141	107862759.12	43058737.10	2			
108	36	3	48	120	84942981.88	20257032.61	32			
109	37	1	12	138	89674416.97	34262480.48	43	266784	89214	0.33441
110	37	2	12	138	76663733.21	40312565.41	43			
111	37	3	6	141	91321954.07	37426705.68	43			
112	38	1	12	138	106138210.69	34104813.87	43	286284	43092	0.15052
113	38	2	12	138	96299764.95	39930815.13	43			
114	38	3	12	138	104516487.03	34914225.93	43			
115	39	1	12	138	115190807.31	34459563.74	2	298440	16500	0.05529
116	39	2	12	138	107098959.87	40376617.47	2			
117	39	3	24	132	112368914.56	30378427.10	2			
118	40	1	12	138	77513298.51	33693128.84	43	240084	127902	0.53274
119	40	2	24	132	51525196.86	33877375.71	43			
120	40	3	3	142	84544118.92	38358513.65	43			
121	41	1	12	138	104458768.41	34284378.62	43	279570	53496	0.19135
122	41	2	24	132	86626986.43	34435909.67	43			
123	41	3	6	141	104969441.84	37278170.59	43			
124	42	1	12	138	115132508.53	34391679.50	2	298488	15720	0.05266
125	42	2	24	132	106661937.13	35020064.45	2			
126	42	3	12	138	113972052.42	34990168.68	2			
127	43	1	12	138	92006432.25	33966855.59	40	254877	84651	0.33212
128	43	2	48	120	59326466.76	22733839.84	40			
129	43	3	3	142	108926384.74	38528826.44	40			
130	44	1	12	138	90007555.57	33916489.87	40	250788	90606	0.36129
131	44	2	48	120	56154364.34	22805578.15	40			
132	44	3	6	141	107685984.63	37263652.12	40			
133	45	1	12	138	59829947.51	33504804.83	40	187296	185820	0.99212
134	45	2	48	120	15415739.50	22723591.51	40			
135	45	3	48	120	77842615.70	20078343.78	40			
136	46	1	24	132	59634720.15	29230938.54	43	234054	145371	0.62110
137	46	2	3	142	69545266.19	44393391.71	43			
138	46	3	12	138	67822376.11	34748938.77	43			
139	47	1	24	132	73297402.13	29165244.12	43	242553	119043	0.49079
140	47	2	3	142	80192577.52	44322934.44	43			
141	47	3	24	132	68120904.09	29779819.55	43			
142	48	1	24	132	112877850.56	29555031.01	2	276639	39222	0.14178
143	48	2	3	142	107883447.28	44633586.93	2			
144	48	3	48	120	84733287.72	20221294.84	2			
145	49	1	24	132	74288864.44	29112688.58	43	256584	102120	0.39800
146	49	2	6	141	78602831.74	42942162.35	43			
147	49	3	6	141	88145835.42	37311674.75	43			
148	50	1	24	132	93159082.35	29248457.05	43	275490	60978	0.22134
149	50	2	6	141	94492806.05	42935757.15	43			
150	50	3	12	138	99382523.99	34878488.17	43			
151	51	1	24	132	109303059.08	29655762.46	43	290604	28332	0.09749
152	51	2	6	141	104914511.38	43244488.07	43			
153	51	3	24	132	108035844.60	30382894.32	43			

Table A-1: continued.

DEVICE LEVEL STATISTICS							FACTORY LEVEL STATISTICS			
OBS	RUN	DEV	LS	REL RATE	NET PROFIT	OPERATING EXPENSE	BNK WC	TOTAL TPUT	TOTAL WIP	CYCLE TIME
154	52	1	24	132	64133756.38	29090790.44	43	240516	130836	0.54398
155	52	2	12	138	63908826.38	39976932.62	43			
156	52	3	3	142	83298438.43	38442274.04	43			
157	53	1	24	132	95746534.28	29248457.05	43	278304	54840	0.19705
158	53	2	12	138	93634389.27	40102474.65	43			
159	53	3	6	141	104291351.13	37253600.88	43			
160	54	1	24	132	112121322.15	29581308.78	2	296940	18348	0.06179
161	54	2	12	138	106702309.77	40435545.36	2			
162	54	3	12	138	113290905.12	35088447.54	2			
163	55	1	24	132	79411046.57	29182762.63	43	250416	102540	0.40948
164	55	2	24	132	66342536.80	34179701.43	43			
165	55	3	3	142	94371000.13	38460142.92	43			
166	56	1	24	132	109539639.78	29340429.24	43	291996	23934	0.08197
167	56	2	24	132	103736104.59	35189161.89	43			
168	56	3	6	141	113440118.51	37426705.68	43			
169	57	1	24	132	78283826.08	29046994.16	40	228888	113496	0.49586
170	57	2	24	132	61877235.88	34359047.20	40			
171	57	3	48	120	82846827.65	19863917.20	40			
172	58	1	24	132	64875850.77	28972540.49	40	219999	143709	0.65323
173	58	2	48	120	32015953.95	22549369.91	40			
174	58	3	3	142	102806432.42	38431664.39	40			
175	59	1	24	132	50632310.88	29274734.82	40	188784	191808	1.01602
176	59	2	48	120	12715334.27	22436638.29	40			
177	59	3	24	132	86388332.73	29672606.25	40			
178	60	1	24	132	78283826.08	29046994.16	40	228888	113496	0.49586
179	60	2	24	120	61877235.88	34359047.20	40			
180	60	3	48	120	82846827.65	19863917.20	40			
181	61	1	48	120	93667460.27	20043780.27	43	276063	53325	0.19316
182	61	2	3	142	97145992.36	44541992.49	43			
183	61	3	6	141	104104629.73	37454625.80	43			
184	62	1	48	120	109681013.49	20525539.35	2	292731	19866	0.06786
185	62	2	3	142	107167203.84	44679704.41	2			
186	62	3	12	138	113363793.92	35139820.57	2			
187	63	1	48	120	108279491.63	20026261.75	2	287661	19458	0.06764
188	63	2	3	142	107967729.71	44869298.51	2			
189	63	3	24	132	111781447.43	30159533.29	2			
190	64	1	48	120	93490476.06	19378076.81	43	275868	48903	0.17727
191	64	2	6	141	97023980.26	42971626.30	43			
192	64	3	3	142	106493938.38	38607002.80	43			
193	65	1	48	120	108881335.08	19964946.96	2	292818	17058	0.05825
194	65	2	6	141	107061796.57	43044645.65	2			
195	65	3	6	141	114887938.42	37487013.15	2			
196	66	1	48	120	109190704.99	20035021.01	2	291462	16848	0.05781
197	66	2	6	141	107853859.02	43221429.33	2			
198	66	3	12	138	114008285.81	35037074.50	2			
199	67	1	48	120	108859234.98	20183928.36	2	292743	18825	0.06431
200	67	2	12	138	106815576.45	40617453.21	2			
201	67	3	3	142	115527419.13	38840415.07	2			
202	68	1	48	120	108608359.77	20087576.55	2	291168	17856	0.06133
203	68	2	12	138	106945380.40	40440669.53	2			
204	68	3	6	141	115146071.60	37485896.35	2			

Table A-1: continued.

DEVICE LEVEL STATISTICS							FACTORY LEVEL STATISTICS			
OBS	RUN	DEV	LS	REL RATE	NET PROFIT	OPERATING EXPENSE	BNK WC	TOTAL TPUT	TOTAL WIP	CYCLE TIME
205	69	1	48	120	108608359.77	20087576.55	40	291168	17856	0.06133
206	69	2	12	138	106945380.40	40440669.53	40			
207	69	3	48	141	126909290.99	25722676.96	40			
208	70	1	48	120	61963725.69	19579539.70	40	235392	117783	0.50037
209	70	2	24	132	56622489.92	34394916.35	40			
210	70	3	3	142	106240264.53	38590250.72	40			
211	71	1	48	168	-21096384.67	32043960.99	40	168672	443280	2.62806
212	71	2	24	180	-35217779.32	48860433.47	40			
213	71	3	24	180	78746232.75	43132341.80	40			
214	72	1	48	168	-36807408.84	31632275.95	40	125832	508344	4.03986
215	72	2	24	180	-51456166.92	48732329.35	40			
216	72	3	48	168	45674755.50	33104758.94	40			
217	73	1	48	168	-29078721.39	31588479.67	40	144036	478800	3.32417
218	73	2	48	168	-58949502.82	37071252.84	40			
219	73	3	12	186	75563459.39	47954042.75	40			
220	74	1	48	168	-35983235.68	31702350.00	40	127944	501600	3.92047
221	74	2	48	168	-64682803.78	37040507.85	40			
222	74	3	24	180	65231774.10	42757095.27	40			
223	75	1	48	168	-47097632.23	31754905.54	40	96192	552048	5.73902
224	75	2	48	168	-70836236.22	37265971.10	40			
225	75	3	48	168	35167167.57	33354923.29	40			
226	76	1	3	191	-18597829.65	44310501.50	19	115875	497697	4.29512
227	76	2	3	191	-32696839.45	50585944.82	19			
228	76	3	24	180	-23171661.72	38075448.13	19			
229	77	1	3	191	20486123.22	49022433.77	19	212211	384999	1.81423
230	77	2	6	189	21724734.83	55744888.00	19			
231	77	3	12	186	26650989.29	46178322.58	19			
232	78	1	3	191	21248076.14	49019696.50	19	210564	387840	1.84191
233	78	2	12	186	18331329.17	53025618.18	19			
234	78	3	6	189	26788535.10	48467441.29	19			
235	79	1	3	191	-8413449.11	45132229.20	19	132609	469452	3.54012
236	79	2	24	180	-21679370.72	43013761.48	19			
237	79	3	3	191	-14502728.43	44810855.35	19			
238	80	1	3	191	36479325.30	50385045.53	40	175212	426132	2.43209
239	80	2	48	168	-45619527.11	37214729.46	40			
240	80	3	48	168	47746938.43	32979676.76	40			
241	81	1	6	189	44479097.00	48350323.53	19	224586	372591	1.65901
242	81	2	3	191	18897119.75	58072349.54	19			
243	81	3	12	186	23376301.89	47132074.17	19			
244	82	1	6	189	67816630.01	50086846.03	19	324768	257274	0.79218
245	82	2	6	189	80993948.26	64673745.10	19			
246	82	3	6	189	90340899.85	56276142.83	19			
247	83	1	6	189	58377660.93	49443040.72	19	250167	229444	0.91716
248	83	2	12	186	80452659.82	32032769.18	19			
249	83	3	3	191	40406256.16	51597121.78	19			
250	84	1	6	189	55388487.41	49291943.55	19	258402	281100	1.08784
251	84	2	24	180	66240698.70	49900638.92	19			
252	84	3	48	168	55156955.73	32890332.35	19			
253	85	1	6	189	53585213.41	48986464.50	40	219888	351078	1.59662
254	85	2	48	168	-21208157.82	37235226.11	40			
255	85	3	24	180	78139612.89	42931316.88	40			

Table A-1: continued.

DEVICE LEVEL STATISTICS							FACTORY LEVEL STATISTICS			
OBS	RUN	DEV	LS	REL RATE	NET PROFIT	OPERATING EXPENSE	BNK WC	TOTAL TPUT	TOTAL WIP	CYCLE TIME
256	86	1	12	186	40786619.45	45853165.98	19	222525	373464	1.67830
257	86	2	3	191	16936497.95	57751448.72	19			
258	86	3	6	189	26468657.82	49354184.57	19			
259	87	1	12	186	49171408.06	46398429.67	19	236571	353112	1.49263
260	87	2	6	189	23933549.81	56958034.01	19			
261	87	3	3	191	34323875.53	50930389.11	19			
262	88	1	12	186	81092694.25	46895517.44	19	282396	237900	0.84243
263	88	2	12	186	82207027.98	55346864.81	19			
264	88	3	48	168	54931272.94	33158365.58	19			
265	89	1	12	186	85147614.59	46983110.00	19	290028	232968	0.80326
266	89	2	24	180	67892845.04	49828900.61	19			
267	89	3	24	180	72646587.25	43163612.34	19			
268	90	1	12	186	48766616.22	46928364.65	40	224496	351684	1.56655
269	90	2	48	168	-17928677.19	37932112.52	40			
270	90	3	12	186	82580943.90	47931706.65	40			
271	91	1	24	180	-8744149.33	36115713.76	19	118821	482403	4.05991
272	91	2	3	191	-32996327.56	50844074.62	19			
273	91	3	3	191	-23708528.21	44459061.73	19			
274	92	1	24	180	98417027.75	42461794.73	19	290652	220092	0.75724
275	92	2	6	189	82695103.41	58340277.45	19			
276	92	3	48	168	55041175.64	33149431.14	19			
277	93	1	24	180	89249955.44	42453035.47	19	293124	227088	0.77472
278	93	2	12	186	70446347.91	55200826.12	19			
279	93	3	24	180	71006603.65	43159145.12	19			
280	94	1	24	180	73387061.61	42255952.21	19	273456	263856	0.96489
281	94	2	24	180	46733390.29	49418967.43	19			
282	94	3	12	186	75012083.19	47922772.20	19			
283	95	1	24	180	18599281.49	41441341.40	40	196596	396492	2.01679
284	95	2	48	168	-36742590.16	37347957.74	40			
285	95	3	6	189	85984734.41	50311286.58	40			
286	96	1	48	168	11864352.10	32114035.03	40	201846	377565	1.87056
287	96	2	3	191	20672096.08	59257312.64	40			
288	96	3	48	168	49445475.32	33274513.32	40			
289	97	1	48	168	45417499.80	32946164.35	19	252486	296334	1.17367
290	97	2	6	189	44838047.76	57818893.69	19			
291	97	3	24	180	72769024.93	43293161.74	19			
292	98	1	48	168	45635609.33	32560757.09	19	237408	325284	1.37015
293	98	2	12	186	42939998.57	54821637.93	19			
294	98	3	12	186	45151529.21	47755251.43	19			
295	99	1	48	168	2681305.45	31991405.45	40	202128	387228	1.91576
296	99	2	24	180	-11612769.78	48778446.83	40			
297	99	3	6	189	84117734.79	50320221.02	40			
298	100	1	48	168	-28228809.56	31605998.19	40	156768	463875	2.95899
299	100	2	48	168	-56452811.66	37891119.20	40			
300	100	3	3	191	89610788.04	51703776.67	40			
301	101	1	3	191	-62696.94	47145763.17	19	169236	410607	2.42624
302	101	2	3	191	11123994.96	53151229.80	19			
303	101	3	48	168	11667745.11	29879425.69	19			
304	102	1	3	191	27625692.30	50370811.74	19	241776	348336	1.44074
305	102	2	6	189	46784182.82	58274944.35	19			
306	102	3	24	180	43592082.98	43418243.92	19			

Table A-1: continued.

DEVICE LEVEL STATISTICS							FACTORY LEVEL STATISTICS			
OBS	RUN	DEV	LS	REL RATE	NET PROFIT	OPERATING EXPENSE	BNK WC	TOTAL TPUT	TOTAL WIP	CYCLE TIME
307	103	1	3	191	29145915.37	50340154.34	19	242115	347940	1.43709
308	103	2	12	186	40829548.22	55077846.16	19			
309	103	3	12	186	47321681.87	47969678.02	19			
310	104	1	3	191	29955330.92	50377928.64	19	236988	354039	1.49391
311	104	2	24	180	34307228.33	49659803.17	19			
312	104	3	6	189	47573903.48	50200722.87	19			
313	105	1	3	191	89095.07	46543564.32	19	151023	438663	2.90461
314	105	2	48	168	-7623367.96	33689304.10	19			
315	105	3	3	191	2590457.11	45902532.37	19			
316	106	1	6	189	57233573.54	49482457.37	19	236778	354801	1.49845
317	106	2	3	191	32160350.47	59211195.15	19			
318	106	3	24	180	20742597.04	42850906.91	19			
319	107	1	6	189	67978602.31	49507640.23	19	265980	304038	1.14309
320	107	2	6	189	43800520.25	57876540.54	19			
321	107	3	12	186	47675550.65	47931706.65	19			
322	108	1	6	189	67946195.82	49440850.90	19	265344	305058	1.14967
323	108	2	12	186	40985116.24	55177767.38	19			
324	108	3	6	189	49817718.00	50305702.55	19			
325	109	1	6	189	63625767.40	49447420.34	19	253257	324645	1.28188
326	109	2	24	180	30693213.41	49772534.80	19			
327	109	3	3	191	46891273.33	51636768.36	19			
328	110	1	6	189	33364971.61	49322600.95	40	171726	432756	2.52004
329	110	2	48	168	-47947816.93	37501682.68	40			
330	110	3	48	168	47632650.98	32908201.23	40			
331	111	1	12	186	57150820.24	46915225.77	19	248937	333996	1.34169
332	111	2	3	191	35668350.76	59241299.62	19			
333	111	3	12	186	36843083.71	47777587.54	19			
334	112	1	12	186	65173319.98	47061943.31	19	264174	307968	1.16578
335	112	2	6	189	41586060.01	57984148.00	19			
336	112	3	6	189	49075525.96	50391696.55	19			
337	113	1	12	186	61112760.27	47094790.52	19	255618	322332	1.26099
338	113	2	12	186	34508690.70	55008669.94	19			
339	113	3	3	191	46513579.86	51600472.20	19			
340	114	1	12	186	63052230.88	46838582.28	40	231924	326496	1.40777
341	114	2	24	180	17690233.50	49055151.73	40			
342	114	3	48	168	51484846.43	33042217.85	40			
343	115	1	12	186	35908184.16	46842961.91	40	204204	380232	1.86202
344	115	2	48	168	-37301937.87	37142991.15	40			
345	115	3	24	180	85583914.95	43105538.48	40			
346	116	1	24	180	50679341.60	41787332.02	19	246183	333534	1.35482
347	116	2	3	191	35552896.65	59182371.73	19			
348	116	3	6	189	42217824.65	50267731.17	19			
349	117	1	24	180	55991107.36	42330405.89	19	251658	327675	1.30206
350	117	2	6	189	35690714.81	57994396.33	19			
351	117	3	3	191	45174000.40	51697075.84	19			
352	118	1	24	180	71679840.74	42260331.84	40	257148	279600	1.08731
353	118	2	12	186	52477589.08	55170081.13	40			
354	118	3	48	168	52837989.84	33042217.85	40			
355	119	1	24	180	45034278.47	42115804.12	40	237840	325632	1.36912
356	119	2	24	180	11809233.45	49290863.31	40			
357	119	3	24	180	78872237.89	43056399.05	40			

Table A-1: continued.

DEVICE LEVEL STATISTICS							FACTORY LEVEL STATISTICS			
OBS	RUN	DEV	LS	REL RATE	NET PROFIT	OPERATING EXPENSE	BNK WC	TOTAL TPUT	TOTAL WIP	CYCLE TIME
358	120	1	24	180	11157169.71	41739156.11	40	190128	407496	2.14327
359	120	2	48	168	-44768856.83	37317212.75	40			
360	120	3	12	186	92285079.78	47994247.73	40			
361	121	1	48	168	67861360.19	26166500.21	19	257685	201951	0.78371
362	121	2	3	191	62610905.46	52659950.51	19			
363	121	3	3	191	70829587.17	45795319.08	19			
364	122	1	48	168	33173998.34	25754815.18	40	210156	256800	1.22195
365	122	2	6	189	42835675.01	51133139.72	40			
366	122	3	48	168	65472568.47	26618354.68	40			
367	123	1	48	168	34680586.00	25763574.43	40	239172	234480	0.98038
368	123	2	12	186	38333233.35	49210677.51	40			
369	123	3	24	180	105701521.14	39974016.86	40			
370	124	1	48	168	14467923.02	25798611.46	40	202428	304800	1.50572
371	124	2	24	180	2123960.70	45017309.90	40			
372	124	3	12	186	94970091.62	43004362.37	40			
373	125	1	48	168	-3547342.85	25395685.68	40	161622	348378	2.15551
374	125	2	48	168	-30775223.75	29753945.56	40			
375	125	3	6	189	92849766.04	44601061.89	40			
376	126	1	24	168	91389477.64	38997508.98	19	290484	168360	0.57958
377	126	2	12	168	76249734.39	49600114.04	19			
378	126	3	12	168	82682788.90	43013296.81	19			
379	127	1	24	168	69053452.45	39023786.75	19	262530	222924	0.84914
380	127	2	6	168	57674153.14	51252276.55	19			
381	127	3	6	168	66437425.56	44656902.15	19			
382	128	1	24	168	81813909.20	38971231.21	19	278298	192798	0.69278
383	128	2	12	168	66362810.37	49600114.04	19			
384	128	3	6	168	76645311.95	44732844.90	19			
385	129	1	24	168	80895410.65	38844222.00	19	276756	193812	0.70030
386	129	2	6	168	67702966.45	51291988.83	19			
387	129	3	12	168	73862414.29	43002128.76	19			
388	130	1	24	168	54193553.47	38734731.30	40	245544	255552	1.04076
389	130	2	24	168	22500317.89	45309387.29	40			
390	130	3	24	168	97079958.48	39799795.26	40			
391	131	1	3	144	-12120355.93	32217801.13	19	91035	368289	4.04558
392	131	2	3	144	-30634099.75	37707637.74	19			
393	131	3	3	144	-10470185.55	34184454.44	19			
394	132	1	3	144	36512216.24	37120794.68	43	176376	270438	1.53330
395	132	2	3	144	16401216.64	43316036.07	43			
396	132	3	6	144	23209157.20	37010137.36	43			
397	133	1	3	144	51598465.23	38128656.57	43	199626	241347	1.20900
398	133	2	3	144	32581951.78	44513809.58	43			
399	133	3	12	144	30030585.47	36497855.62	43			
400	134	1	3	144	43413879.74	37818797.89	43	191394	253191	1.32288
401	134	2	6	144	19813904.51	43366186.98	43			
402	134	3	3	144	35887760.87	38634922.92	43			
403	135	1	3	144	52649038.40	38064057.06	43	212577	215868	1.01548
404	135	2	6	144	37013512.64	43796616.82	43			
405	135	3	6	144	48014752.16	38107956.81	43			
406	136	1	3	144	51918186.32	37961683.26	55	251133	141939	0.56519
407	136	2	6	144	103908997.23	44241138.12	19			
408	136	3	48	144	69526551.97	26654092.45	19			

Table A-1: continued.

DEVICE LEVEL STATISTICS							FACTORY LEVEL STATISTICS			
OBS	RUN	DEV	LS	REL RATE	NET PROFIT	OPERATING EXPENSE	BNK WC	TOTAL TPUT	TOTAL WIP	CYCLE TIME
409	137	1	3	144	53502238.94	38069531.60	43	202380	233409	1.15332
410	137	2	12	144	21290940.69	41457816.23	43			
411	137	3	3	144	46180439.27	38770056.35	43			
412	138	1	3	144	49961684.77	37944164.74	55	235764	167469	0.71032
413	138	2	12	144	70467906.00	41775514.45	43			
414	138	3	24	144	69512112.90	32893472.28	43			
415	139	1	3	144	50356682.74	37898178.65	55	252453	139203	0.55140
416	139	2	12	144	109782431.92	42418597.13	19			
417	139	3	48	144	69719534.52	26609420.24	19			
418	140	1	3	144	49731839.20	37868616.16	55	233862	172179	0.73624
419	140	2	24	144	57722375.17	37956210.86	43			
420	140	3	12	144	79147646.43	36468818.69	43			
421	141	1	3	144	49516027.64	37868068.71	55	245832	150684	0.61296
422	141	2	24	144	76717283.43	38217543.26	43			
423	141	3	24	144	86068700.77	33335727.11	43			
424	142	1	3	144	50412000.45	37833031.68	55	252837	140274	0.55480
425	142	2	24	144	113541315.15	39063030.45	40			
426	142	3	48	144	69687898.37	26582616.92	32			
427	143	1	3	144	62307574.10	38000005.00	40	238446	165555	0.69431
428	143	2	48	144	37224610.08	30532818.61	40			
429	143	3	6	144	104982522.75	38238623.01	40			
430	144	1	3	144	63839112.01	38035042.02	40	234525	173745	0.74084
431	144	2	48	144	31386032.81	30512321.95	40			
432	144	3	12	144	103137984.47	36605068.92	40			
433	145	1	3	144	67409044.52	38045443.64	40	222879	194874	0.87435
434	145	2	48	144	15819121.62	29999905.47	40			
435	145	3	24	144	95683581.09	33277653.25	40			
436	146	1	6	144	29561568.05	36019480.90	43	171777	275376	1.60310
437	146	2	3	144	13815508.78	43020756.07	43			
438	146	3	3	144	25869577.49	37597969.35	43			
439	147	1	6	144	58756472.66	37058547.64	43	216036	205407	0.95080
440	147	2	3	144	45570937.51	44463848.97	43			
441	147	3	12	144	42948952.01	36211953.51	43			
442	148	1	6	144	91412284.12	37385924.83	19	268524	107736	0.40122
443	148	2	3	144	98938848.81	44976905.97	19			
444	148	3	48	144	69589828.86	26707699.10	19			
445	149	1	6	144	53016161.93	37196505.92	43	211917	214437	1.01189
446	149	2	6	144	34530462.90	43432801.13	43			
447	149	3	3	144	50080502.45	38797976.48	43			
448	150	1	6	144	85159952.41	37404538.25	43	251454	139608	0.55520
449	150	2	6	144	71037803.31	43901662.20	43			
450	150	3	24	144	62170273.13	33085562.76	43			
451	151	1	6	144	88671331.30	37279718.85	55	272538	100416	0.36845
452	151	2	6	144	109720277.28	44380771.61	2			
453	151	3	48	144	69587045.16	26627289.13	32			
454	152	1	6	144	88024522.26	37478991.93	43	262860	116214	0.44211
455	152	2	12	144	71320812.28	41906180.65	43			
456	152	3	12	144	80438762.34	36321400.41	43			
457	153	1	6	144	87963042.37	37320230.41	43	270342	101892	0.37690
458	153	2	12	144	84121656.55	41967670.63	43			
459	153	3	24	144	86147094.62	33188308.83	43			

Table A-1: continued.

DEVICE LEVEL STATISTICS							FACTORY LEVEL STATISTICS			
OBS	RUN	DEV	LS	REL RATE	NET PROFIT	OPERATING EXPENSE	BNK WC	TOTAL TPUT	TOTAL WIP	CYCLE TIME
460	154	1	6	144	88764026.27	37269864.69	55	272532	99512	0.36514
461	154	2	12	144	111807591.19	42340880.63	2			
462	154	3	48	144	69728250.67	26564748.04	32			
463	155	1	6	144	86805612.36	37339938.74	43	253944	132564	0.52202
464	155	2	24	144	55875766.72	37899845.05	43			
465	155	3	6	144	82801917.49	37999626.71	43			
466	156	1	6	144	88396287.85	37345413.27	43	273168	98514	0.36064
467	156	2	24	144	80287624.31	38601855.62	43			
468	156	3	12	144	95152634.72	36520191.72	43			
469	157	1	6	144	88327973.46	37258915.62	43	278928	87444	0.31350
470	157	2	24	144	90919226.63	38427634.02	43			
471	157	3	24	144	99936748.72	33483145.39	43			
472	158	1	6	144	80219742.38	37240302.20	40	247431	147129	0.59463
473	158	2	48	144	37240060.11	30348348.68	40			
474	158	3	3	144	105042862.07	39089462.62	40			
475	159	1	6	144	79434036.66	37255630.90	40	245388	151152	0.61597
476	159	2	48	144	35517377.45	30450831.97	40			
477	159	3	6	144	104472226.92	38132526.52	40			
478	160	1	6	144	75068463.65	37062927.27	40	237516	165618	0.69729
479	160	2	48	144	29319753.04	30522570.28	40			
480	160	3	12	144	101504327.28	36348203.73	40			
481	161	1	12	144	37196040.55	35617975.34	43	198404	243264	1.22610
482	161	2	3	144	32159447.68	44699560.55	43			
483	161	3	3	144	42593150.44	38798721.01	43			
484	162	1	12	144	77013425.96	31863174.27	43	230133	159232	0.69191
485	162	2	3	144	61950552.24	44517012.18	43			
486	162	3	24	144	48488007.99	33076628.32	43			
487	163	1	12	144	114455775.47	36117252.94	19	281475	84987	0.30193
488	163	2	3	144	103662941.32	45268342.84	19			
489	163	3	48	144	69526551.97	26654092.45	19			
490	164	1	12	144	81401646.17	35674910.51	43	256088	124626	0.48665
491	164	2	6	144	71709392.70	43617271.06	43			
492	164	3	12	144	74831865.87	35714602.95	43			
493	165	1	12	144	91132996.36	35753743.81	43	268272	108328	0.40380
494	165	2	6	144	82539010.37	44002864.46	43			
495	165	3	24	144	79127726.22	33439217.72	43			
496	166	1	12	144	115620011.37	35970535.40	2	282544	75488	0.26717
497	166	2	6	144	108527412.51	42945578.46	2			
498	166	3	48	144	69699361.03	26618354.68	32			
499	167	1	12	144	83051502.13	35865424.33	43	260964	121686	0.46629
500	167	2	12	144	68754170.02	42152140.56	43			
501	167	3	6	144	83218005.48	38065518.22	43			
502	168	1	12	144	97117982.91	35060302.71	43	276408	83212	0.30105
503	168	2	12	144	83660355.12	41693527.81	43			
504	168	3	12	144	92472783.71	36194084.62	43			
505	169	1	12	144	106389783.31	35946447.44	43	288912	68856	0.23833
506	169	2	12	144	94707797.14	42211068.45	43			
507	169	3	24	144	98360465.32	33460809.29	43			
508	170	1	12	144	70243750.17	35388044.87	43	231112	171132	0.74047
509	170	2	24	144	41048750.81	37740995.94	43			
510	170	3	3	144	73047941.43	37968004.12	43			

Table A-1: continued.

DEVICE LEVEL STATISTICS							FACTORY LEVEL STATISTICS			
OBS	RUN	DEV	LS	REL RATE	NET PROFIT	OPERATING EXPENSE	BNK WC	TOTAL TPUT	TOTAL WIP	CYCLE TIME
511	171	1	12	144	95418429.63	35148625.21	43	270168	101042	0.37400
512	171	2	24	144	71238822.40	38437882.35	43			
513	171	3	6	144	93407286.25	38257608.70	43			
514	172	1	12	144	108120439.81	35858854.88	43	292080	61162	0.20940
515	172	2	24	144	93820391.45	38468627.34	43			
516	172	3	12	144	105845373.69	36560024.44	43			
517	173	1	12	144	69083810.05	35490966.13	43	210820	177918	0.84393
518	173	2	48	144	2720276.26	21572362.50	43			
519	173	3	3	144	101738552.73	38945953.16	43			
520	174	1	12	144	68924485.38	35512134.33	43	190338	179454	0.94282
521	174	2	48	144	22347760.70	30235617.05	43			
522	174	3	6	144	55355195.86	23192651.90	43			
523	175	1	12	144	39282857.22	35440600.41	43	169668	300564	1.77148
524	175	2	48	144	-17026323.16	30051147.12	43			
525	175	3	48	144	64063963.78	26511141.39	43			
526	176	1	24	144	51999616.16	32121493.02	43	226956	163945	0.72236
527	176	2	3	144	60279865.27	44525338.95	43			
528	176	3	12	144	69277188.28	32500437.76	43			
529	177	1	24	144	60076778.28	31474767.95	43	229695	173196	0.75403
530	177	2	3	144	66844651.35	43905528.52	43			
531	177	3	24	144	56994944.59	33081095.54	43			
532	178	1	24	144	119463379.48	33098150.06	19	283689	81676	0.28791
533	178	2	3	144	105733406.95	45298447.31	19			
534	178	3	48	144	69567469.64	26554324.52	19			
535	179	1	24	144	64391350.00	32311276.90	43	247294	146622	0.59291
536	179	2	6	144	67988718.57	43817113.48	43			
537	179	3	6	144	77901056.10	38111307.23	43			
538	180	1	24	144	82022119.95	32506900.28	43	266266	109746	0.41217
539	180	2	6	144	81360577.37	43893975.96	43			
540	180	3	12	144	86196638.29	36363094.47	43			
541	181	1	24	144	93891765.18	32612011.36	43	274244	91146	0.33235
542	181	2	6	144	87935197.64	43033970.30	43			
543	181	3	24	144	89630490.46	33152571.07	43			
544	182	1	24	144	56194429.51	32183902.72	43	232074	174345	0.75125
545	182	2	12	144	53213647.63	41675593.24	43			
546	182	3	3	144	73647337.85	38762238.71	43			
547	183	1	24	144	84774696.91	32629529.87	43	269052	105048	0.39044
548	183	2	12	144	78518904.33	41924115.23	43			
549	183	3	6	144	92115537.80	38118008.06	43			
550	184	1	24	144	100831840.27	32743400.20	43	288024	70500	0.24477
551	184	2	12	144	93838897.88	42216192.62	43			
552	184	3	12	144	102595019.46	36698880.55	43			
553	185	1	24	144	67867539.29	32357992.93	43	240126	160777	0.66955
554	185	2	24	144	51647835.96	38008306.54	43			
555	185	3	3	144	82323674.49	38892904.91	43			
556	186	1	24	144	96001345.47	32550696.56	43	273848	49708	0.18152
557	186	2	24	144	95565323.90	29457783.61	43			
558	186	3	6	144	102826842.03	37190315.25	43			
559	187	1	24	144	53478712.41	32105434.38	40	204712	230016	1.12361
560	187	2	24	144	27646518.57	37710250.95	40			
561	187	3	48	144	65895932.23	26511141.39	40			

Table A-1: continued.

DEVICE LEVEL STATISTICS							FACTORY LEVEL STATISTICS			
OBS	RUN	DEV	LS	REL RATE	NET PROFIT	OPERATING EXPENSE	BNK WC	TOTAL TPUT	TOTAL WIP	CYCLE TIME
562	188	1	24	144	43479983.56	32401789.21	40	199680	240636	1.20511
563	188	2	48	144	-1148695.46	29999905.47	40			
564	188	3	3	144	93686512.55	38915799.42	40			
565	189	1	24	144	28907496.29	32042659.72	40	174312	290400	1.66598
566	189	2	48	144	-17444918.15	29907670.51	40			
567	189	3	24	144	81384330.42	33299989.35	40			
568	190	1	24	144	13392173.88	32174048.56	40	144168	352248	2.44332
569	190	2	48	144	-32799966.94	30020402.13	40			
570	190	3	48	144	61318875.87	26636223.57	40			
571	191	1	48	144	104323005.83	26692055.57	19	287082	74376	0.25908
572	191	2	3	144	91827940.31	45043520.11	19			
573	191	3	6	144	99915186.89	38256491.89	19			
574	192	1	48	144	115624560.18	27200092.42	40	302748	50616	0.16719
575	192	2	3	144	100192051.82	45509819.11	40			
576	192	3	12	144	112390497.28	37060725.41	40			
577	193	1	48	144	87982270.05	25976716.33	40	276826	92072	0.33260
578	193	2	3	144	80819796.51	44927372.38	40			
579	193	3	24	144	111680321.98	33521861.30	40			
580	194	1	48	144	107968305.94	26911036.97	19	290676	68844	0.23684
581	194	2	6	144	93582657.18	44203987.92	19			
582	194	3	3	144	102155664.67	39073268.94	19			
583	195	1	48	144	120353193.78	27103740.60	40	308946	36754	0.11897
584	195	2	6	144	104562848.84	44536631.62	40			
585	195	3	6	144	115852725.34	38574781.36	40			
586	196	1	48	144	106377618.73	25937299.68	40	295928	54072	0.18272
587	196	2	6	144	97820173.96	44192458.55	40			
588	196	3	12	144	114815661.71	36761421.64	40			
589	197	1	48	144	85942140.97	26105185.42	40	275430	94494	0.34308
590	197	2	12	144	78841827.47	42131643.90	40			
591	197	3	3	144	109664593.30	39120174.76	40			
592	198	1	48	144	85677182.66	26332926.07	40	273636	97488	0.35627
593	198	2	12	144	76353162.48	41808821.52	40			
594	198	3	6	144	109954325.07	38218520.52	40			
595	199	1	48	144	3612333.18	18306527.83	40	166648	267432	1.60477
596	199	2	12	144	24511666.27	41539802.87	40			
597	199	3	48	144	65882514.43	26680895.77	40			
598	200	1	48	144	37625993.66	25894963.27	40	214146	212832	0.99386
599	200	2	24	144	26760637.33	37884472.55	40			
600	200	3	3	144	97386449.96	38888996.09	40			
601	201	1	48	144	18543750.20	25772333.69	40	183744	271896	1.47975
602	201	2	24	144	6676617.69	37541153.52	40			
603	201	3	24	144	83700408.89	33107898.86	40			
604	202	1	48	144	-1868293.60	25605907.83	40	146712	344976	2.35138
605	202	2	24	144	-13216433.18	37484787.70	40			
606	202	3	48	144	61156729.34	26421796.98	40			
607	203	1	48	144	-5422439.03	25316852.38	40	143664	350256	2.43802
608	203	2	48	144	-32162842.88	29876925.52	40			
609	203	3	12	144	77406576.59	36558163.10	40			
610	204	1	48	144	-10826914.06	25675981.87	40	129840	378000	2.91128
611	204	2	48	144	-39346240.89	29600220.62	40			
612	204	3	24	144	67059803.49	33090029.98	40			

Table A-1: continued.

DEVICE LEVEL STATISTICS							FACTORY LEVEL STATISTICS			
OBS	RUN	DEV	LS	REL RATE	NET PROFIT	OPERATING EXPENSE	BNK WC	TOTAL TPUT	TOTAL WIP	CYCLE TIME
613	205	1	48	144	-23570823.23	25202982.05	40	104016	427248	4.10752
614	205	2	48	144	-47265622.84	29651462.27	40			
615	205	3	48	144	46967169.55	26359255.89	40			
616	206	1	24	144	53695005.32	32178428.18	40	204912	230016	1.12251
617	206	2	24	144	27646518.57	37710250.95	40			
618	206	3	48	144	65895932.23	26511141.39	40			
619	207	1	12	144	95335513.10	35747174.37	40	254124	134916	0.53091
620	207	2	24	144	74586009.97	38058694.16	40			
621	207	3	48	144	68387329.30	26546879.16	40			
622	208	1	12	144	115938871.78	35900461.35	55	284880	76392	0.26816
623	208	2	12	144	112082410.68	42341734.65	2			
624	208	3	48	144	69800244.27	26573682.48	32			
625	209	1	12	144	106389783.31	35946447.44	43	288912	68856	0.23833
626	209	2	12	144	94707797.14	42211068.45	43			
627	209	3	24	144	98360465.32	33460809.29	43			
628	210	1	12	144	95928552.17	35425271.71	43	276408	85212	0.30828
629	210	2	12	144	83660355.12	41693527.81	43			
630	210	3	12	144	92472783.71	36194084.62	43			
631	211	1	3	96	78954782.50	25204374.35	2	210456	9576	0.04550
632	211	2	3	96	73435638.73	29586477.11	2			
633	211	3	48	96	89976220.32	13502595.12	2			
634	212	1	3	96	78797660.27	25170432.23	2	210498	7794	0.03703
635	212	2	6	96	74447868.86	28661115.16	2			
636	212	3	12	96	80772494.97	23270415.54	2			
637	213	1	3	96	78966968.90	25198899.81	2	210408	7812	0.03713
638	213	2	12	96	76132566.80	26756587.54	2			
639	213	3	6	96	79057347.04	24871582.29	2			
640	214	1	3	96	79018768.93	25204374.35	2	210540	8313	0.03948
641	214	2	24	96	79764486.03	23044891.41	2			
642	214	3	3	96	78313337.51	25723538.70	2			
643	215	1	3	96	78906085.90	25202731.98	40	210501	11781	0.05597
644	215	2	48	96	86974314.38	15693237.46	40			
645	215	3	48	96	90020882.01	13440054.03	40			
646	216	1	6	96	79626842.19	24339013.02	2	210312	7827	0.03722
647	216	2	3	96	73435414.10	29592241.80	2			
648	216	3	12	96	80599049.01	23243612.22	2			
649	217	1	6	96	79780747.37	24358721.35	2	210468	7350	0.03492
650	217	2	6	96	74381157.32	28631651.22	2			
651	217	3	6	96	79152777.68	24870465.49	2			
652	218	1	6	96	79674157.54	24354341.72	2	210408	7791	0.03703
653	218	2	12	96	76116902.87	26764273.78	2			
654	218	3	3	96	78356470.91	25722421.90	2			
655	219	1	6	96	79927991.19	24329158.86	2	210666	8946	0.04247
656	219	2	24	96	80147269.18	22947532.28	2			
657	219	3	48	96	90339124.81	13422185.15	2			
658	220	1	6	96	79955808.30	24353246.81	2	210684	9306	0.04417
659	220	2	48	96	87358894.51	15549760.85	2			
660	220	3	24	96	83922891.43	19920663.77	2			
661	221	1	12	96	81202013.29	22739679.21	2	210414	7803	0.03708
662	221	2	3	96	73295421.98	29570464.10	2			
663	221	3	6	96	79259864.12	24927422.55	2			

Table A-1: continued.

DEVICE LEVEL STATISTICS							FACTORY LEVEL STATISTICS			
OBS	RUN	DEV	LS	REL RATE	NET PROFIT	OPERATING EXPENSE	BNK WC	TOTAL TPUT	TOTAL WIP	CYCLE TIME
664	222	1	12	96	81375091.48	22776906.05	2	210525	7650	0.03634
665	222	2	6	96	74318768.60	28622683.93	2			
666	222	3	3	96	78372007.25	25728564.32	2			
667	223	1	12	96	81451524.88	22711211.63	2	210492	8868	0.04213
668	223	2	12	96	76413983.61	26697659.64	2			
669	223	3	48	96	90192503.21	13404316.27	2			
670	224	1	12	96	81506704.57	22717781.07	2	210648	8100	0.03845
671	224	2	24	96	80162034.63	22962904.77	2			
672	224	3	24	96	83996202.23	19929598.21	2			
673	225	1	12	96	81371972.39	22715591.26	2	210384	9168	0.04358
674	225	2	48	96	87115459.45	15488270.87	2			
675	225	3	12	96	80768423.46	23187771.96	2			
676	226	1	24	96	84213788.46	19561449.85	2	210267	8530	0.04057
677	226	2	3	96	73281603.72	29580071.91	2			
678	226	3	3	96	78255563.06	25720746.69	2			
679	227	1	24	96	84619155.32	19525682.89	2	210666	9162	0.04349
680	227	2	6	96	74657535.02	28603468.31	2			
681	227	3	48	96	90226489.85	13431119.59	2			
682	228	1	24	96	84454721.24	19495025.50	2	210480	8208	0.03900
683	228	2	12	96	76393996.85	26684849.23	2			
684	228	3	24	96	84042688.67	19929598.21	2			
685	229	1	24	96	84673230.01	19543201.40	2	210648	8196	0.03891
686	229	2	24	96	80069847.99	22962904.77	2			
687	229	3	12	96	80819825.42	23185538.35	2			
688	230	1	24	96	84249989.77	19586997.68	40	210516	10974	0.05213
689	230	2	48	96	86777701.49	15744479.11	40			
690	230	3	6	96	79221383.97	24860414.24	40			
691	231	1	48	96	90564843.32	13141486.54	2	210390	10716	0.05093
692	231	2	3	96	73423750.97	29530111.30	2			
693	231	3	48	96	90206827.77	13440054.03	2			
694	232	1	48	96	90677412.72	13132727.28	2	210468	9306	0.04422
695	232	2	6	96	74640790.38	28606030.39	2			
696	232	3	24	96	83776269.83	19902794.89	2			
697	233	1	48	96	90677412.72	13132727.28	2	210540	8928	0.04241
698	233	2	12	96	76408762.30	26700221.72	2			
699	233	3	12	96	80808659.99	23201173.63	2			
700	234	1	48	96	90677412.72	13132727.28	2	210636	9188	0.04362
701	234	2	24	96	80048962.74	22973153.10	2			
702	234	3	6	96	79328284.15	24854085.68	2			
703	235	1	48	96	57135993.06	12948782.91	40	168021	91056	0.54193
704	235	2	48	96	41864311.38	14873371.10	40			
705	235	3	3	96	72493405.80	25595664.51	40			
706	236	1	3	96	78954782.50	25204374.35	2	210456	9576	0.04550
707	236	2	3	96	73435638.73	29586477.11	2			
708	236	3	48	96	89976220.32	13502595.12	2			
709	237	1	3	96	79013504.48	25198899.81	2	210468	8202	0.03897
710	237	2	6	96	74361619.81	28607311.43	2			
711	237	3	24	96	83812081.22	19992139.30	2			
712	238	1	3	96	79143589.37	25224082.67	2	210792	7680	0.03643
713	238	2	12	96	76351692.29	26784770.44	2			
714	238	3	12	96	80820315.79	23259247.49	2			

Table A-1: continued.

DEVICE LEVEL STATISTICS							FACTORY LEVEL STATISTICS			
OBS	RUN	DEV	LS	REL RATE	NET PROFIT	OPERATING EXPENSE	BNK WC	TOTAL TPUT	TOTAL WIP	CYCLE TIME
715	239	1	3	96	78983363.72	25186308.38	2	210390	8229	0.03911
716	239	2	24	96	79669773.55	22978277.27	2			
717	239	3	6	96	79159939.96	24888334.37	2			
718	240	1	3	96	78997938.42	25203279.44	2	210420	9417	0.04475
719	240	2	48	96	86897961.31	15549760.85	2			
720	240	3	3	96	78300136.33	25697852.18	2			
721	241	1	6	96	79706069.44	24360911.16	2	210498	8298	0.03942
722	241	2	3	96	73535839.55	29610816.90	2			
723	241	3	24	96	83792419.14	20001073.74	2			
724	242	1	6	96	79851883.02	24368575.51	2	210450	7530	0.03578
725	242	2	6	96	74312284.37	28591938.94	2			
726	242	3	12	96	80743423.85	23241378.61	2			
727	243	1	6	96	79814869.29	24343392.65	2	210480	7368	0.03500
728	243	2	12	96	76205665.18	26720718.38	2			
729	243	3	6	96	79226088.48	24879399.93	2			
730	244	1	6	96	79743960.91	24354341.72	2	210378	8055	0.03828
731	244	2	24	96	79822818.96	22993649.76	2			
732	244	3	3	96	78284038.30	25686684.13	2			
733	245	1	6	96	79726022.22	24393758.37	40	210372	12360	0.05875
734	245	2	48	96	86492495.93	15703485.79	40			
735	245	3	48	96	90128179.44	13475791.80	40			
736	246	1	12	96	81358908.26	22752818.09	2	210540	7818	0.03713
737	246	2	3	96	73534758.84	29605692.73	2			
738	246	3	12	96	80672359.81	23252546.66	2			
739	247	1	12	96	81377301.49	22755007.91	2	210438	7434	0.03532
740	247	2	6	96	74425538.47	28609873.52	2			
741	247	3	6	96	79094880.64	24849246.19	2			
742	248	1	12	96	81389715.16	22770336.61	2	210495	7800	0.03705
743	248	2	12	96	76146069.33	26738652.96	2			
744	248	3	3	96	78357471.69	25714045.86	2			
745	249	1	12	96	81521328.25	22711211.63	2	210696	9072	0.04305
746	249	2	24	96	80040317.09	22932159.79	2			
747	249	3	48	96	90485746.41	13440054.03	2			
748	250	1	12	96	81449314.87	22733109.77	40	210516	9672	0.04594
749	250	2	48	96	87216291.73	15529264.19	40			
750	250	3	24	96	83886236.03	19916196.55	40			
751	251	1	24	96	84264158.90	19538821.78	2	210321	8244	0.03919
752	251	2	3	96	73428796.36	29581352.95	2			
753	251	3	6	96	79073884.17	24869348.68	2			
754	252	1	24	96	84327982.71	19551960.66	2	210387	8067	0.03834
755	252	2	6	96	74323807.70	28591938.94	2			
756	252	3	3	96	78389317.07	25710137.04	2			
757	253	1	24	96	84410395.67	19473127.36	2	210324	9300	0.04421
758	253	2	12	96	76371848.68	26661790.49	2			
759	253	3	48	96	90212165.29	13395381.83	2			
760	254	1	24	96	84547792.40	19495025.50	2	210552	9568	0.04544
761	254	2	24	96	80086410.41	22932159.79	2			
762	254	3	24	96	83623230.94	20120199.62	2			
763	255	1	24	96	83704431.01	19643932.85	40	209472	13536	0.06462
764	255	2	48	96	85323600.50	15734230.78	40			
765	255	3	12	96	80699606.17	23219042.51	40			

Table A-1: continued.

DEVICE LEVEL STATISTICS							FACTORY LEVEL STATISTICS			
OBS	RUN	DEV	LS	REL RATE	NET PROFIT	OPERATING EXPENSE	BNK WC	TOTAL TPUT	TOTAL WIP	CYCLE TIME
766	256	1	48	96	90374280.98	13185282.82	2	210195	9696	0.04612
767	256	2	3	96	73257251.73	29580712.43	2			
768	256	3	3	96	78155533.40	25692268.16	2			
769	257	1	48	96	90805060.33	13159005.05	2	210720	10212	0.04846
770	257	2	6	96	74555172.79	28568880.20	2			
771	257	3	48	96	90373111.45	13448988.47	2			
772	258	1	48	96	90696910.95	13123968.03	2	210612	9204	0.04370
773	258	2	12	96	76518774.28	26702783.81	2			
774	258	3	24	96	84006033.27	19925130.99	2			
775	259	1	48	96	90824558.57	13150245.79	40	210600	9348	0.04439
776	259	2	24	96	79998546.60	22952656.44	40			
777	259	3	12	96	80809994.38	23190005.57	40			
778	260	1	48	96	55175180.72	12747320.02	40	167664	92646	0.55257
779	260	2	48	96	43143492.60	15262807.62	40			
780	260	3	6	96	72857166.83	24784471.49	40			
781	261	1	3	96	78778518.61	25267878.95	2	210399	8898	0.04229
782	261	2	3	96	73181099.75	29711378.63	2			
783	261	3	3	96	78003836.55	25784962.98	2			
784	262	1	3	96	78969178.91	25177001.67	2	210222	9330	0.04438
785	262	2	6	96	74279693.58	28574004.36	2			
786	262	3	48	96	89927909.13	13440054.03	2			
787	263	1	3	96	79000311.04	25168242.41	2	210402	8299	0.03944
788	263	2	12	96	76250424.90	26743990.63	2			
789	263	3	24	96	83741439.18	19960868.76	2			
790	264	1	3	96	79055604.37	25185213.47	2	210534	8175	0.03883
791	264	2	24	96	79894120.35	23003898.09	2			
792	264	3	12	96	80721515.01	23230210.56	2			
793	265	1	3	96	78867902.51	25154556.08	2	210132	9303	0.04427
794	265	2	48	96	86788483.39	15467774.21	2			
795	265	3	6	96	79115666.10	24850362.99	2			
796	266	1	6	96	79623072.64	24330253.76	2	210207	9372	0.04458
797	266	2	3	96	73345157.96	29526268.18	2			
798	266	3	48	96	90035206.56	13475791.80	2			
799	267	1	6	96	79676367.55	24332443.58	2	210390	8070	0.03836
800	267	2	6	96	74421847.11	28606030.39	2			
801	267	3	24	96	83878229.74	19983204.86	2			
802	268	1	6	96	79851655.75	24347772.28	2	210456	7512	0.03569
803	268	2	12	96	76267422.43	26713032.14	2			
804	268	3	12	96	80722849.39	23219042.51	2			
805	269	1	6	96	79901960.88	24356531.53	2	210540	7740	0.03676
806	269	2	24	96	79935890.85	22983401.43	2			
807	269	3	6	96	79163943.11	24854830.21	2			
808	270	1	6	96	79936537.33	24382809.30	2	210654	9018	0.04281
809	270	2	48	96	87082334.59	15549760.85	2			
810	270	3	3	96	78424515.50	25707345.03	2			
811	271	1	12	96	81230155.64	22737489.40	2	210318	8430	0.04008
812	271	2	3	96	73414122.02	29580071.91	2			
813	271	3	24	96	83787925.62	19960868.76	2			
814	272	1	12	96	81410318.40	22750628.28	2	210534	7524	0.03574
815	272	2	6	96	74422296.36	28594501.02	2			
816	272	3	12	96	80818069.03	23239145.00	2			

Table A-1: continued.

DEVICE LEVEL STATISTICS							FACTORY LEVEL STATISTICS			
OBS	RUN	DEV	LS	REL RATE	NET PROFIT	OPERATING EXPENSE	BNK WC	TOTAL TPUT	TOTAL WIP	CYCLE TIME
817	273	1	12	96	81434691.19	22739679.21	2	210528	7404	0.03517
818	273	2	12	96	76305234.54	26728404.63	2			
819	273	3	6	96	79192101.85	24852596.60	2			
820	274	1	12	96	81396799.73	22746248.65	2	210627	8013	0.03804
821	274	2	24	96	79929771.04	23009022.26	2			
822	274	3	3	96	78465085.63	25717954.68	2			
823	275	1	12	96	77472082.33	22763767.16	40	202140	27768	0.13737
824	275	2	48	96	77049766.96	15570257.51	40			
825	275	3	48	96	87555275.94	13377512.94	40			
826	276	1	24	96	84378287.84	19560719.92	2	210348	8382	0.03985
827	276	2	3	96	73378289.11	29546764.84	2			
828	276	3	12	96	80670113.05	23232444.17	2			
829	277	1	24	96	84440552.11	19543201.40	2	210444	7860	0.03735
830	277	2	6	96	74534020.51	28618840.81	2			
831	277	3	6	96	79049728.58	24838078.14	2			
832	278	1	24	96	84366979.18	19534442.15	2	210393	8127	0.03863
833	278	2	12	96	76289570.60	26736090.88	2			
834	278	3	3	96	78283810.21	25678866.50	2			
835	279	1	24	96	84675440.02	19521303.26	2	210648	9456	0.04489
836	279	2	24	96	80082087.59	22911663.13	2			
837	279	3	48	96	90378448.97	13404316.27	2			
838	280	1	24	96	77513380.72	19477506.98	40	198648	33312	0.16769
839	280	2	48	96	72519914.86	15488270.87	40			
840	280	3	24	96	81657555.67	19893860.45	40			
841	281	1	48	96	90432775.69	13159005.05	2	210273	9270	0.04409
842	281	2	3	96	73387742.13	29550607.96	2			
843	281	3	6	96	79070970.23	24854830.21	2			
844	282	1	48	96	91282892.48	13404264.22	2	211194	9000	0.04261
845	282	2	6	96	74457497.81	28611154.56	2			
846	282	3	3	96	78416475.03	25716279.47	2			
847	283	1	48	96	90735907.43	13106449.51	2	210516	10152	0.04822
848	283	2	12	96	76412720.69	26664352.57	2			
849	283	3	48	96	90305138.17	13395381.83	2			
850	284	1	48	96	90363622.79	13106449.51	40	210240	10248	0.04874
851	284	2	24	96	79881151.89	22942408.11	40			
852	284	3	24	96	83979208.91	19916196.55	40			
853	285	1	48	96	53418630.89	12983819.93	40	163440	101688	0.62217
854	285	2	48	96	38291086.91	15078337.69	40			
855	285	3	12	96	72890728.26	23134165.32	40			
856	286	1	3	96	78847201.30	25221345.40	2	210474	8184	0.03888
857	286	2	3	96	73282283.88	29644764.49	2			
858	286	3	6	96	79057837.41	24945291.43	2			
859	287	1	3	96	78689363.95	25206016.71	2	210210	8379	0.03986
860	287	2	6	96	74113874.50	28689298.07	2			
861	287	3	3	96	78132201.77	25731914.74	2			
862	288	1	3	96	79059260.29	25183571.11	2	210678	9126	0.04332
863	288	2	12	96	76280026.47	26718156.30	2			
864	288	3	48	96	90348111.84	13502595.12	2			
865	289	1	3	96	79035488.98	25165505.15	2	210429	8505	0.04042
866	289	2	24	96	79910682.78	22973153.10	2			
867	289	3	24	96	83837080.83	19938532.65	2			

Table A-1: continued.

DEVICE LEVEL STATISTICS							FACTORY LEVEL STATISTICS			
OBS	RUN	DEV	LS	REL RATE	NET PROFIT	OPERATING EXPENSE	BNK WC	TOTAL TPUT	TOTAL WIP	CYCLE TIME
868	290	1	3	96	79170009.56	25204374.35	2	210411	9210	0.04377
869	290	2	48	96	86951971.42	15478022.54	2			
870	290	3	12	96	80679031.72	23196706.40	2			