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The Applicability Of Simulation To Study The Introduction Of A Minimum Lot Size Decision Rule For Products In Decline.

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THE APPLICABILITY OF SIMULATION
TO STUDY THE INTRODUCTION OF A
MINIMUM LOT SIZE DECISION RULE
FOR PRODUCTS IN DECLINE

by

John Wayne Nazemetz

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respite from the pressures of this task.

I must thank my parents for providing the opportunity for much of my education and their continuing encouragement and understanding during the final years of my graduate study. I would also like to thank all of my friends and relatives who gave me encouragement and support and Mrs. Marcia Mielnik who endured my terrible penmanship while typing and editing the manuscript.

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ABSTRACT

Extensive efforts to improve the production and inventory control procedures for products in the maturity phase of product life cycle have been made since the early 1900's; the problem of production and inventory control for products in the declining stages of the product life cycle, however, has been ignored. This dissertation investigates the use of simulation to gauge the economic effect of the introduction of a minimum manufacturing lot size decision rule for products in the decline phase of product life using data from an actual industrial situation.

The type of inventory-production problem studied in this paper is found in many industries particularly the transportation, agricultural, and industrial and consumer durable industries. These types of industry produce (original) equipment which will later require repair and/ or replacement products. As the original equipment ages, less and less of the original equipment remains in use and hence the demand for the repair/replacement parts decreases. The production of these low demand and/or infrequently demanded products presents many production problems when they compete for the limited productive

capability of the manufacturing facility with higher
volume items.

Simulation experiments were performed for various
levels of the decision rule to gauge the economic effect
of the decision rule for the low or infrequently demanded
items. A forty-five week period was simulated and from
the data generated, the transient and long-term effects
of the introduction of the rule on the number of setups,
inventory levels and customer service which occurred in
the simulation experiments was observed and/or estimated.
These estimates were obtained through the generation of
time series for each of the major parameters to be
observed under several levels of the decision rule. The
differences between the time series for the decision rule
and the base or current policy were determined and
families of curves fit to this data. The curves fit to
the data were of an asymtotic nature and the asymtotes
were used to estimate the long term effects of the deci-
sion rule introduction. Random sampling of manufacturing
sequence for the products under study provided the factors
necessary for the conversion of observed parameter values
into dollar terms.

The investigation indicated that the use of a simula-
tion is good methodology for the study of this problem
and that the use of a minimum manufacturing lot size

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decision rule would yield economic benefits to the firm which is manufacturing products in the declining phase of their life when compared to the usual make to order policy for the products.

CHAPTER 1. INTRODUCTION

1.1 Introduction

The problem of inventory control is one that frequently arises in operations management. Simply stated, the problem of inventory control is the determination of the optimum balance of the set of costs which increase with the amount of product that is manufactured or purchased at a time and the set of costs that decrease as the amount of product manufactured or purchased is increased.

Typically, there are four types of business operations. One type of business is the kind which manufactures different types of products for unique customer orders, these orders are usually being made only one time for the customer who does not reorder. This type of manufacturing operation is called the job shop.

The two other types of manufacturing businesses are continuous manufacturing and intermittent, or batch manufacturing. In the continuous manufacturing situation, the product is being made continuously and is demanded at the same average rate that it is manufactured; in the intermittent or batch manufacturing situation, the rate at which the product can be produced exceeds the rate at which the product is demanded. This difference in the production and consumption rates means that the product, once manufactured, usually must wait some period of time before it is consumed and that continuous

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production of the item would build inventory which would never be used.

The fourth type of business is the retail type which does not manufacture, but resellsthe already manufactured product to final consumers or to retailers. In this situation, the demand rate and the rate at which the product is obtained will, in general, not be equal.

The inventory problem does not arise in the job shop situation. The job shop, by definition (3) produces a sequence of unique items, none of which is expected to be reordered. It is therefore unwise to produce more of a product than is demanded as the creation of an inventory for the product will not yield any benefit to the manufacturer. The product that is produced and inventoried will not be ordered again so all of the material and labor expended for the product will be lost; in addition the space used to store the item will be lost to alternate use until the product (inventory) is disposed of. There is also an opportunity cost associated with producing more product than the customer demands--the additional time that was spent in the manufacture of the inventory (which is worthless) could have been used to produce another product which presumably would have made a positive contribution to profit; doing nothing is still preferred to wasting materials in addition to labor which would happen if an inventory of

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this item were to be made.

The continuous manufacturing situation does not usually have an inventory problem. Since all of the product that can be produced is consumed; there is no possibility of a (long run) build-up of inventory. In the short run, however, an inventorying problem may arise if demand is seasonal or otherwise varying (this variation usually can be described stochastically). If demand varies, one of two strategies must be adopted. A strategy of continuous production with inventory build-up during the periods of low demand and inventory depletion during the periods of high demand may be adopted if the demand fluctuations are not too severe and/or the period of the seasonality is relatively short (3). The alternate strategy is one which would involve the varying of the production rate of the product to correspond to the demand rate; this strategy usually calls for adjustment of the workforce as the production rate is usually a function of workforce (49, 50). The models used to analyze these situations are known as single product models with seasonal (deterministically varying) and/or stochastic demand and aggregate planning models.

The intermittent or batch manufacturing situation is beset with inventory problems. In this type of manufacturing, the production rate exceeds the consumption or demand rate; therefore, in order to avoid a constantly

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increasing inventory, the production of the product must be suspended for some period of time so that cumulative demand can "catch up" to cumulative production, e.g. if a product is demanded at a rate of ten (10) units per time period and the product can be produced at the rate of twenty (20) units per time period, then the production of this product can be in operation at most, one half (.5) of the time to avoid inventory build-up in the long run. It is this intermittent nature of the manufacturing process which gives it its name; the alternate name of batch manufacturing is derived from the amount of product or batch size that is produced during a period of production.

The batch size that should be produced during a period of manufacture is determined through analysis of several costs and conditions. If the product is the only one which is produced on a piece or series of equipment, it is known as a dedicated machine problem and one of two strategies may be adopted. One strategy would be to hold no inventory and produce the product as it is demanded; this strategy is used when customers demand the product individually or in small lots and are willing to wait the length of time it takes to manufacture the amount of goods that they have demanded plus any additional amount of product that had been demanded

previous to their order and for which manufacturing is
not yet complete. This strategy breaks down when
customers are not willing to wait or if there is a
start-up cost associated with restarting the manufacturing
equipment after it has been turned off. In either of
the preceding situations the alternate strategy of
inventory maintenance may be preferred. Under an inven-
tory maintenance policy, some amount (the batch size) of
the product is made at once and stored; this inventory
is used to satisfy customer demand without delay for
manufacturing and spreads the start-up cost over more
than one item, thereby lowering the per unit manufacturing
cost and increasing profit. A reduction in profit occurs
however, when the cost of storing this inventory is
considered. It is intuitive that the best or optimum
batch size is the one that balances the increase in
profit due to better customer service and the lowering of
the per unit manufacturing costs and the decrease in
profit due to storage cost. This is known as the
economic manufacturing lot size problem.

Additional complications arise in batch manufactur-
ing when additional products are manufactured on the
same equipment. In this case, there may be a set-up
cost associated with the readying of the equipment for
the manufacture of one product after another has been

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in production; as in the previous case with a start-up cost, it is desirable to spread the set-up cost over several units of production. Also in this case, either inventory or backordering must be used to satisfy the customer demand during the period during which other products are being set up and manufactured on the equipment. This class of problems is known as the single machine, multi-product model.

Further refinements in lot sizing models can be made when multi-period considerations are taken into account. The frequencies of production runs for all products produced on the same equipment must be the same or integral multiples of the base cycle length. Flexibility must be included in the scheduling of the various products if the demand rate(s) of the product(s) in question is seasonal and/or stochastic. Capacity must be taken into account in determining the lot sizes and may have to be varied in response to demand. Various strategies which attempt to quantify and balance the costs of inventory, setup, overtime production, changing workforce levels and loss and/or deferred sales must be weighed under these conditions. This class of problems are known as multi-product, multi-period lot sizing/scheduling problems and problems of aggregate planning.

The models that are used in the solution of the lot sizing problems in intermittent manufacturing constituted

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the background of the problem under study and are discussed in detail in Appendix I.

The wholesaler-retailer situation has inventory problems similar to those of the batch manufacturing situation. In this situation, a merchant must meet the demand placed upon him/her by his/her customers. Again, two strategies evolve; the merchant can order exactly enough to fill the customers' demand if the customer is willing to wait until the merchant can receive the order. If the customers are unwilling to wait for the receipt of their order, or if the placement of an order by the merchant has an associated cost (in either time, dollars, or both), the maintenance of an inventory is justifiable. The sales that result from being able to satisfy customer's demand immediately add to profit as does the spreading out of the cost of placing an order over several items (thereby lowering their unit cost). Of course, as in the batch manufacturing situation the storage cost incurred by ordering more than current needs reduces profit and the contributions and deductions to profit must be balanced. The class models useful in the wholesaler-retailer situation are known as the economic order quantity models (EOQ).

CHAPTER 2. THE PROBLEM AND ITS ENVIRONMENT

2.1 Problem Description

The problem under investigation is the determination of the applicability of simulation to the study of the economic effects of a minimum manufacturing batch size decision rule in intermittent manufacturing facilities which operate under the following conditions:

a. The manufacturing facility is producing a number of products, the manufacture of which requires that similar machining operations be performed on each product;

b. Each product made requires completion of a series of manufacturing operations, each operation requiring some set-up time, the time required being dependent upon the processing sequence of the products through each operation;

c. The production facility is at, or is approaching its capacity,

d. some of the products to be manufactured are in the decline phase of the product life cycle, are ordered infrequently, are produced for a market which must be served, and have undertain future sales, and

e. little historical data exists for use in solution.

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Situations in which the above conditions are met occur frequently in the industrial sector. Typical industries that fit the above conditions are those which produce parts for consumer or industrial durables. These industries will produce parts for the original sales of the durables and may also furnish replacement parts; as the product ages more variability in sales occurs (the coefficient of variation increases) as sales volume drops. If the original marketing strategy included the assurance of replacement parts, the manufacture of these parts in small quantities must be undertaken which often requires more planning effort in relation to the batch size and profit potential. Examples of industries which must deal with this type of problem are those which manufacture original and replacement parts for the transportation field (auto, trucks, buses, trains, and airplanes), consumer durables (washers, dryers, ranges) or industrial and agricultural capital equipment (machine tools, pumps, tractors).

New firms entering an established market or established firms expanding their product lines into the types of industries described above may also meet many of the aforementioned conditions. As these firms try to gain a market share they may introduce a number of products, some of which may sell well while others would sell poorly; the actual sales of the products being difficult

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to estimate at the time of introduction, and usually the production facility is near its capacity at this time as the least possible capital investment is made in order to reduce risk as much as possible.

The problem studied is one which occurs when a firm is producing a number of goods, some of which are in the extremes of product life. The product life cycle is shown in Figure 1.
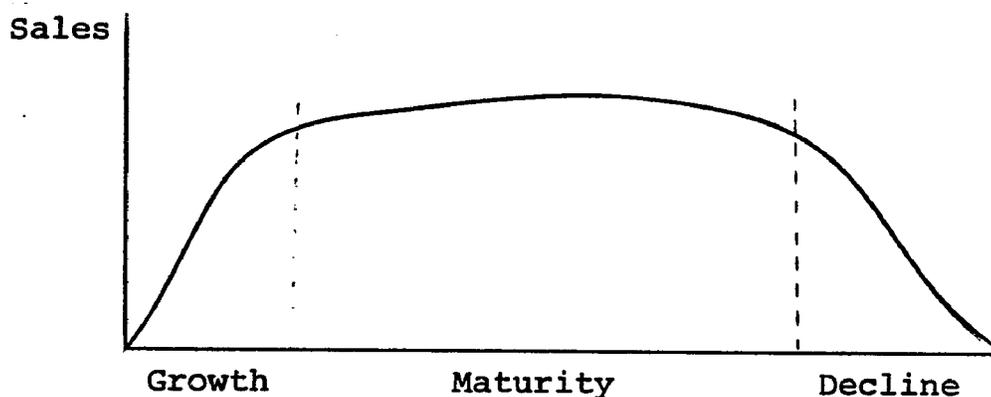
Figure 1. Typical Product Life Cycle.

The life cycle of the typical product has three phases, growth, maturity and decline. The growth phase deals with the penetration of the product into the market—as the consumers become increasingly aware of the product its sales may increase. The rate of growth is difficult to predict and the point (in time) where sales begin to level off and the magnitude of this level are very difficult to predict. During this phase of the product's life the demand rate is changing

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and difficult to predict and therefore most of the inventory models which exist are of limited use in formulation of an inventory policy during the growth phase.

During product maturity, demand has stabilized and becomes much easier to predict; this ability to predict or anticipate demand enables the use of the currently existing models in formulation of inventory policies. The duration of this period of the product's life may be quite long if the product achieves high consumer preference or may never occur as in the case of products that do not penetrate the market.

The decline phase of the product's life cycle is again marked by the inability to predict demand and use any of the existing inventory models which are designed for use during the steady state conditions of the product maturity phase. The thrust of this study will be directed toward problems associated with manufacturing of products in the decline stage of their life.

Although this type of problem is fairly widespread in industry, it has not been addressed in the literature. The existing models can be used as a basis in hypothesis of possible solutions, however, the assumption of demand predictability which serves as the basis for the existing models is usually violated during the decline

phase of the product's life.

The classic economic manufacturing lot size model can be used to gain insight into the problem by incorporating into it a cost of capacity or the opportunity cost of using capacity in the setting up for a small batch given that the facility is at capacity. The formulation of this extension of the Wilson Model can be expressed as:

min total cost = set-up costs + inventory
carrying costs

where the set-up cost would consist of two components:
a) the cost of set-up labor, materials incurred during the physical setting up of the machine(s), and
b) an opportunity cost associated with the setup which, having been made forced other products to be produced in overtime. The first component is the set-up charge normally incorporated into the classic model and the second component is additive when overtime production is being used. Mathematically this extension can be expressed as:

$$\min \quad TC = \left[(S)(T) + (O)T \right] \frac{D}{Q} + Q(1 - D/M)CC \qquad (1)$$

where

      TC = Total cost

      S = Set-up rate ($/hour)

      O = Overtime rate ($/hour)

      T = Set-up time (hours)

D = Demand (units/year)

Q = Lot size (units)

M = Manufacturing rate (units/year)

CC = Carrying cost (\$/unit/year)

Differentiating with respect to the lot size,

$$\frac{TC}{Q} = - \frac{(S)(T) + (O)(T)D}{Q^2} + CC(1 - D/M) \qquad (2)$$

equating the derivative to zero and solving for the optimum lot size,

$$Q^* = \sqrt{\frac{(S)(T) + (O)(T)D}{CC(1 - D/M)}} \qquad (3)$$

or

$$Q^* = \sqrt{\frac{(S)(T)(D)}{CC(1 - D/M)} + \frac{(O)(T)(D)}{CC(1 - D/M)}} \qquad (4)$$

The first term of the right-hand side of equation 4 is the expression for the optimum batch quantity under normal conditions and the second term is the addition to the batch quantity that is justified under conditions when overtime must be used. For example, if

S = 10 \$/hour

T = 2 hours

D = 100 units/year

M = 25,000 units/year

O = 5 \$/hour

CC = 5 \$/unit/year

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Then

$$Q^* = \sqrt{\frac{(10)(2)(100)}{(5)(1 - \frac{100}{25,000})} + \frac{(5)(2)(100)}{(5)(1 - \frac{100}{2500})}}$$

$$= \sqrt{401.6 + 208.8}$$

$$= \sqrt{610.4} = 24.7$$

This means that a twenty-three (23) percent increase in lot size is justified when working in an overtime situation.

Increasing all batch sizes as implied by the above example would not necessarily be the preferred strategy, however; an increase in all batch sizes would reduce throughput in terms of the number of different products manufactured per unit time and enormous (short term) scheduling problems and shortage problems would occur. The increase in batch size may also reduce set-up time sufficiently so that the manufacturing facility will be under capacity and the larger batch sizes would no longer be economically justified as the condition which justified the increase in batch size would no longer exist. In view of the above, the products which would yield the most benefits from an increase in their lot sizes without creating unduly large scheduling problems would be those which have relatively small batch sizes. The products meeting the criteria for small batch sizes are generally those which exhibit a low yearly demand.

One of the problems of the classical model is its assumption of a constant demand rate. This assumption does not always hold in industrial situations especially in the case of low demand items, the class of items which may provide the improvement in inventory management sought. The case in which items are ordered infrequently is the one which most often violates this assumption.

Infrequent demand can pose one of the major problems in the study of inventory control in the industrial sector. The low density of information in time may make it difficult, if not impossible to build or fit stochastic distributions to the demand pattern, that is to the empirical data, with any degree of confidence. If the industry uses a relatively short data retention period (e.g. a year), there may not be enough data points available for any type of curve fitting or distribution fitting to the empirical data. This lack of data for a reasonable length of time may preclude the use of any mathematically sophisticated forecasting techniques and seasonality determination, and require the analysis to be made through direct use of the existing empirical data without building any stochastic distributions.

The inability to accurately forecast demand precludes the use of the model which requires a knowledge of future demand such as the Wagner-Whitin algorithm and

other dynamic programming formulations, as well as the
linear programming and network modelling formulations.

2.2 Background of Case Study

The firm from which the data was drawn for this study is one that produces original equipment and replacement parts in the field of transportation. The family of parts that was used for the study were those that have most of their sales in the automobile replacement market, that is, the automobiles requiring these parts are, in general, the older automobiles, the function of these parts being performed by a new style of parts (which are also produced by the firm but will not be included in this study) in the newer automobiles. These parts are used or worn out during normal automobile operation and must be replaced periodically. This particular firm does not market all of its product under its own brand; a large portion of its production is sold to distributors who sell the parts under their own brand names.

The particular product lines to be studied were those for which a large portion of the line was in the decline stage of the product life cycle. The selection of the product lines to be studied was made by examination of the age of the automobiles for which these products were being made and sales volume. Operating personnel identified the products in decline on the basis of their experience; the firm did not retain more than one year's sales data and product sales histories could not be obtained.

The management of this firm has decided on a policy of maintaining a high quality and service reputation in the market; management believes that the provision of a high quality, complete line of products will maintain and perhaps enhance the firm's reputation in the market and lead to a larger market share. This policy means that products will be manufactured for (almost) any automobile in existence that is desired, which means that a large number of parts, those for older and less numerous models and makes of automobiles will be ordered and manufactured in small batch quantities infrequently.

The adherence to this policy produced the desired effect of increasing sales volume. This increase in sales volume, however, created some operational difficulties as the increase in the production required to meet this demand began to approach the limit to the productive capability of the manufacturing areas which produced this type of product. The manufacturing of the product in question requires forming operations involving heat and pressure and a series of machining operations (such as grinding, drilling, etc.) to insure both material properties and dimentional integrity. Each of the products that is produced requires a similar series of operations, each of these operations requiring some set-up time on each of the machine tools used in its production. This set-up

time for a particular part is dependent upon the part that preceded it upon the machine tool; grouping of parts by similar dimensional characteristics for processing at each machine tool reduces total set-up times as a major set-up cost may be incurred for example a different product diameter is set up but adjustments or setups for varying widths or lengths within diameter may be relatively minor.

The acquisition of additional capital equipment was considered and rejected for this manufacturing area, as a substantial portion of the products made in this area are in the latter stages of product life and sales for these products is expected to decline. This decision was reinforced by the preference of automobile manufacturers to equip their new models with the new style product rather than the older style produced in this area; this preference was interpreted to mean that capital investment would be much less risky in the new style product.

The problem faced by this firm was to economically produce this product in a manner that would minimize production costs and produce sufficient product to satisfy all the demand without increasing capital investment. The small batches of infrequently ordered items were judged to be the main source of problems which decreased operational efficiency as the time and effort required in scheduling

and setup are much higher for these "small runners," than for the large batch size products.

This firm uses a weighted moving average as its primary forecasting methodology. This method was selected as it will react to trends in sales, and provides a simple forecasting function which is easy to calculate and understand, and requires relatively small amounts of data. The sales of the last six (6) months are weighted and averaged, this average being used as the estimate of the current value of the demand rate. The estimate is calculated by the following:

$$D_t = \sum_{i=1}^{6} W_i D_{t-7+i} \Big/ \sum_{i=1}^{6} W_i \quad \text{for } t = 1, 2, 3, \ldots N \quad (5)$$

where

D_t = the estimate of demand rate for period t

D_{t-7+i} = the observed demand for period t-7+i

W_i = the weight applied to the demand observed in period i

This estimate of the demand rate D_t is used in the determination of the batch sizes of the products manufactured and the inventory maintained via its incorporation in the firm's inventory policy.

The inventory policy used by the firm is a modified (S,s) type of policy. The policy is modified from the strict policy which determined S and s on an individual product basis by the aggregation of products into classes

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based upon their usage and variability in demand and determining S and s for the product's usage class and applying this S and s policy to each product in the class. For example, a particular usage class may have an S and s which corresponds to four (4) months estimated demand and two (2) months estimated demand respectively. Thus, for a product in this usage class having a monthly usage of D_t, S would equal $4D_i$ and s would equal $2D_t$. The multiples of D_t to determine S and s are usage class dependent.

This inventory policy determination procedure has some highly interesting assumptions. Consider the general case of the Wilson Model. The optimum lot size is

$$Q^* = \sqrt{(D)(SU)/(CC)(1 - D/M)}$$

where

Q* = the optimum batch size

D = the demand rate

SU = the set-up cost

CC = the carrying cost

M = manufacturing rate

substituting

$$\alpha D = Q^*$$

where α is the percentage of demand that is included in the optimum lot size,

$$\alpha D = \sqrt{(D)(SU)/CC(1 - D/M)}$$

solving for α

$$\alpha = \sqrt{(D)(SU)/CC(1 - D/M)(\tfrac{1}{D})}$$

replacing D by its estimator D_t

$$\alpha_t = \sqrt{(D_t)(SU)/(CC)(1 - D_t/M)(\tfrac{1}{D_t})}$$

or

$$\alpha_t = \sqrt{SU/CC(1 - D_t/M)(\tfrac{1}{D_t})} \qquad (6)$$

The above result shows that the proportion of demand that should be included in the optimum lot size is roughly inversely proportional to the square root of the estimate of the demand rate. This relationship of demand and order quantity indicates that as usage of an item falls more of the estimated demand should be included in the lot size; examining this relationship as demand decreases, or finding the limit of the right-hand side of equation (6) as D_t approaches zero:

$$\lim_{D_t \to 0} \sqrt{(SU)/CC(1 - D_t/M)(\tfrac{1}{D_t})} = \infty$$

therefore

$$\lim_{D_t \to 0} \alpha_t = \infty$$

Or, as demand decreases all of the demand which would occur over an infinite time horizon should be made during the one setup for the product, regardless of set-up and carrying charges.

Under the firm's current estimating/inventory practices, the low demand item class has a (0,0) policy, that is only the amount of product manufactured will be the amount that has been demanded and backordered. This implies that the expected amount of demand over an infinite planning horizon is zero. This current practice will, for items demanded infrequently (in this case infrequently is on the order of two (2) orders placed for the item per year), implicitly assumes that the current order is the last order which will be received for the particular good; for if no orders have been received for an item in the last six (6) months, that is

$$D_i = 0 \quad \text{for } i = t-6, \; t-6, \; t-4, \; \ldots, \; t-1$$

then

$$D_t = \frac{\sum\limits_{i=1}^{6} W_i \, D_{t-7+i}}{\sum\limits_{i=1}^{6} W_i} = \emptyset$$

and

$$S = \alpha_t \, D_t = \emptyset$$

This policy of manufacturing only for backorder will also apply to infrequently ordered items regardless of annual demand as long as the estimate of demand rate (D_t) remains in the rage which has a (0,0) policy.

Under the previous business conditions when some capacity was still available, the above policy was

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considered both reasonable and prudent as it produced
the product demanded and did not build inventory for any
item which had uncertain future sales. However, under
the current operating conditions which is an over
capacity situation, the assumption of additional risk in
producing more than orders on hand may be justified on
the basis that this increase in inventory will increase
the production capability of the manufacturing facility
by reducing set-up time and increase customer service.
An increase in inventory is also more in keeping with
the concept that some reordering will occur for the low
demand or infrequently demanded.

In view of the previous results obtained by exten-
sion of the classic manufacturing lot sizing model for
situations in which production facilities are over
capacity, and the deductions resulting from considera-
tion of the implicit assumptions of a usage class (S,s)
policy, an investigation of the effect of increases in
batch sizes, at least for the smaller batch sizes seems
warranted. The discussion of the possible methods of
investigation will be deferred until after discussion of
the order entry/production-inventory system.

2.3 Order Entry/Production-Inventory System Description

The order/entry/production inventory system of the firm used in the case study performs the seven basic functions of systems of this type:

1. Receipt and recording of orders upon entry into the system,

2. Determination of the availability of products ordered by customers,

3. Maintenance of a record of backlogged orders,

4. Updating of inventory records to reflect the assignment product from finished goods inventory or work-in-process to arriving customer orders, raw material usage and changes in status of work in process,

5. Determination of the products that must be produced and the quantities of the goods to be produced either for customer orders or maintenance of inventory or both,

6. Maintenance of the component-finished goods relationships and methods of manufacture (bill of materials and routing).

7. Maintain records of product in transit and on order, and generate billing documents.

The firm's order entry/production-inventory system executes the above functions within a central manufacturing site-warehouse and regional warehouse configuration: terminals are used for data entry, editing, printing, and file inquiry at the remote (warehouse) locations; this system configuration results in no loss of generality as all files and all processing is performed at the central site. The inventory

files are maintained separately for each warehouse and the central site, and all inventory replenishment requests from the warehouses are processed in the same manner as the customer orders that are received at the central site with minor changes in the billing and accounting procedures. There is no transshipment of goods among the remote warehouses; all orders received at a warehouse are filled from the warehouse inventory previously received from the central site or from additional products received from the central site.

Most order entry systems are similar to the one described above. Most multi-warehousing operations operate in much the same manner as above with all data processing done at a central site; some however allow for transshipment which may be included as an extension of this study with little difficulty. The multi-manufacturing warehousing system can be studied using the results of the analysis obtained for this system by applying the results to each manufacturing facility or make an abstraction by aggregating all manufacturing into one facility. The results will be applicable to a single warehousing facility directly.

Order Receipt at Remote Locations (Warehouses)

The receipt of orders is the most important event in any business, serving as the basis of profit and satisfaction of which constitutes the justification for

an order entry/production-inventory system. Order receipt is shown in Figure 2 at the remote sites. These orders may be received by either mail or phone. The source document used for data entry into the system is an order form generated by an order clerk either during the phone conversation with the customer or sales person or from the letter received from the customer or salesperson. The data which describes the order (customer, part numbers, quantities, etc.) is keyed onto floppy disk at the remote site and transmitted via phone line from the terminal to the central site for processing.

At the central site, the order is recorded and the inventory status of the items ordered at the particular warehouse ascertained to determine the availability of the item at the warehouse. If at least some of the desired item is available at shipping document is gen- erated to be used in order picking and the inventory status updated to indicate the allocation of product to customer order (which has not yet been picked and shipped). If the item is not available in sufficient quantity, the required quantity, customer, part number, etc. are recorded on the open or outstanding order file. The inventory status of the item is checked at the completion of processing of the order and if the
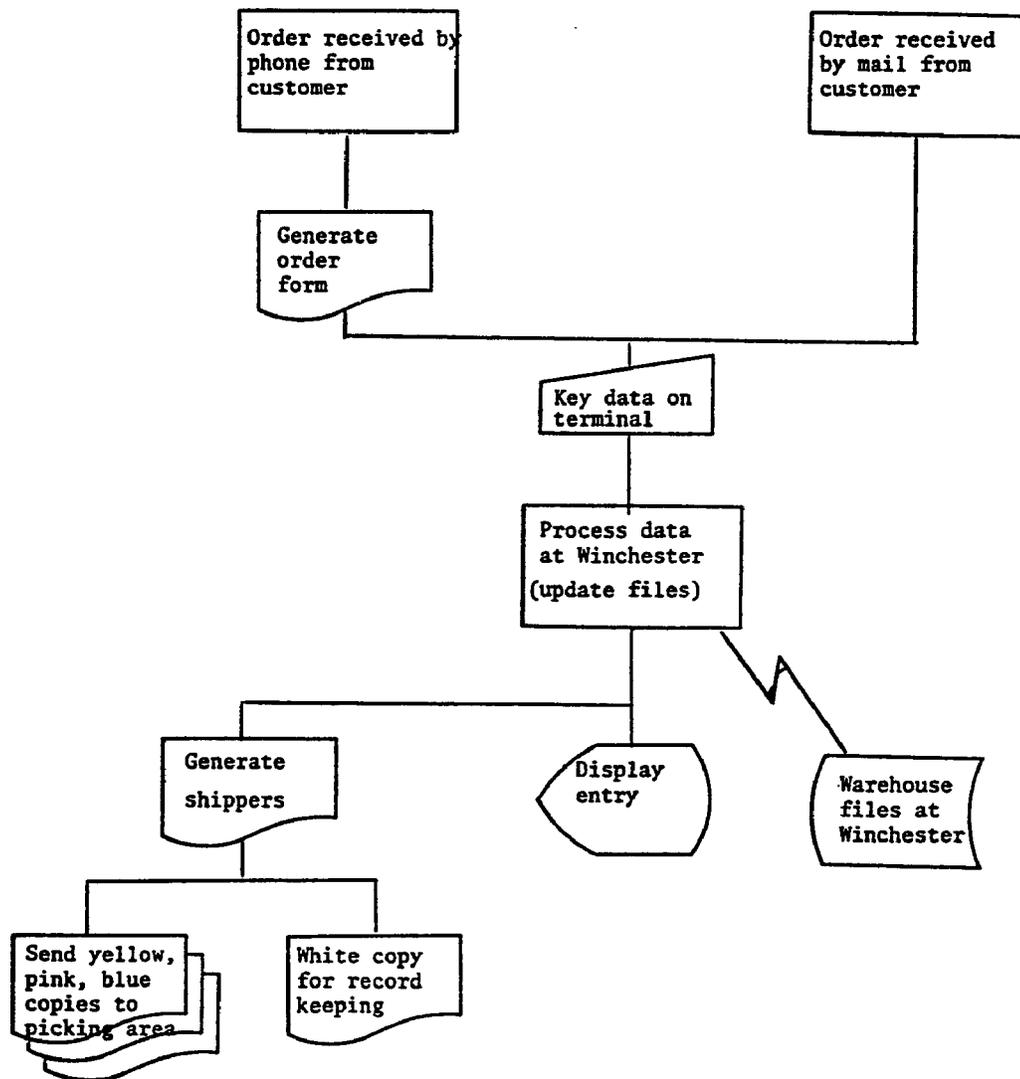
Figure 2. Order Entry at Remote Sites

reorder point is reached, an order for additional
product is placed against the central site and processed
in the same manner as a customer order received at the
central site.

Order Receipt at Central Site

Orders may be received at the central site from
customers or salespersons by phone or mail as in a
similar manner to the remote sites, and the processing
procedure for these orders shown in Figure 3. As at
the remote sites, the letter or phone conversation is
used by an order entry clerk to generate an order form.
The central site however, has the ability to process
rush and non-rush (normal) orders.

The order clerk will, with any assistance necessary
from his/her supervisor, determine whether the order
is rush or normal and process it accordingly; all rush
orders for the warehouses are entered via phone to the
central site rather than by terminal. If the order is
determined to be a rush order, the "in-stock-list"
which is a daily printout of the inventory that is
available at the central site, is used to determine the
inventory status of the product which constitutes the
rush order. If the product is not available in
inventory the order form is sent to data processing and
the order is processed as a regular order; this regular
process assures that the product will be shipped as soon

Order received by phone from customer

Order received by mail from customer

Generate order form

In stock list

Check if order can be filled from stock. Update in stock list.

Order cannot be filled from stock

Order can be filled from stock

Send order form to data processing

DP 3

Updated in stock list

From order prepare shipper. (Hand typed)

Send yellow, pink, and blue copies of shipper to whse.

Sent white copy of shipper to data processing

W 1

DP 1

Figure 3. Order Entry at Central Site

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as product becomes available. If product is available for the rush order, the in-stock-list is manually updated and a picking-shipping document (shipper) is hand typed and burst, three parts of the form being sent to the warehouse for picking and later return for record keeping and one part sent to data processing for use as a source document in file updating.

In data processing (Figure 4), the white copy of the shipping document for the rush order is received and used to key the data describing the order. After keying, this data is used to update the open order file, which contains the records of outstanding (unshipped) orders. A printout of the data is obtained and the printout and white copy of the shipper returned to the order department for error checking (Figure 5).

Processing of Regular Orders - Generation of Recommended for Production List

After receipt of the order, generation of the order form, determination of rush/non-rush character and inventory status (if rush) of the order at the central site is completed, the major processing of the order and the generation of the recommended for production list must be undertaken. The completed order forms are received by data processing and used for the keying of the data necessary for file maintenance. This procedure is shown in Figure 6.

The file maintenance performed on the open order
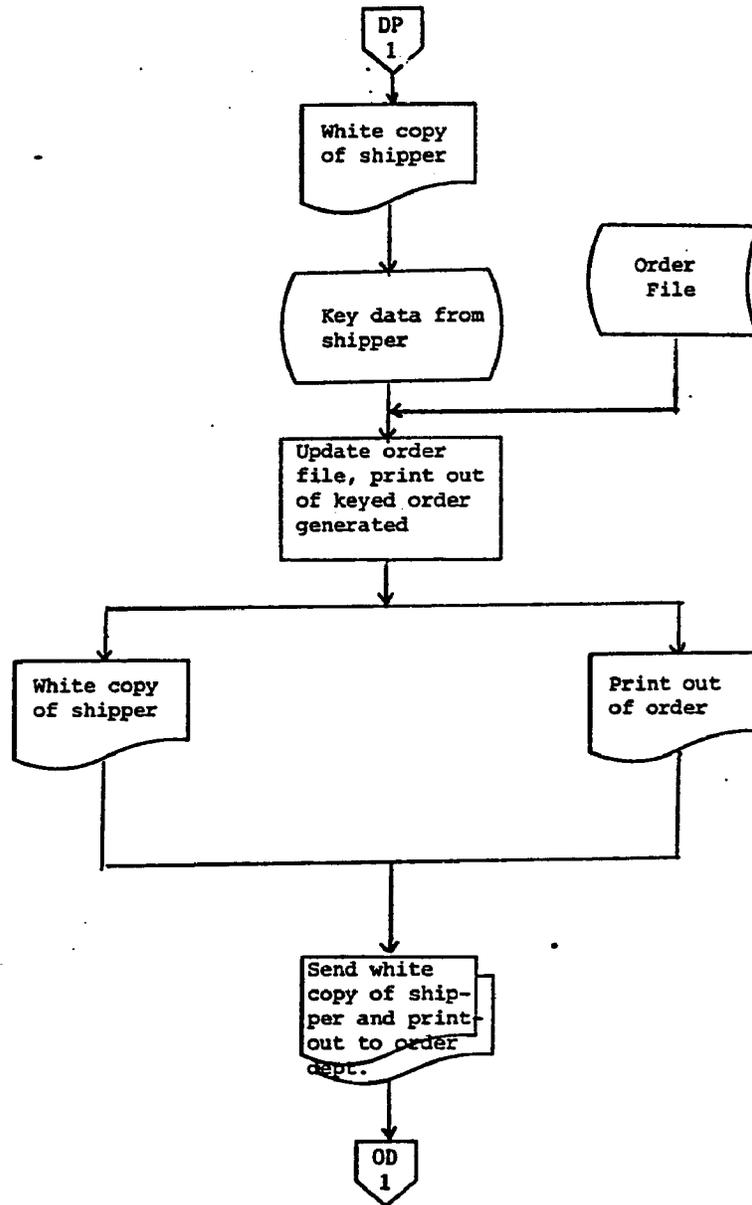
Figure 4. Keying of Data from Shipper
(Rush Order)

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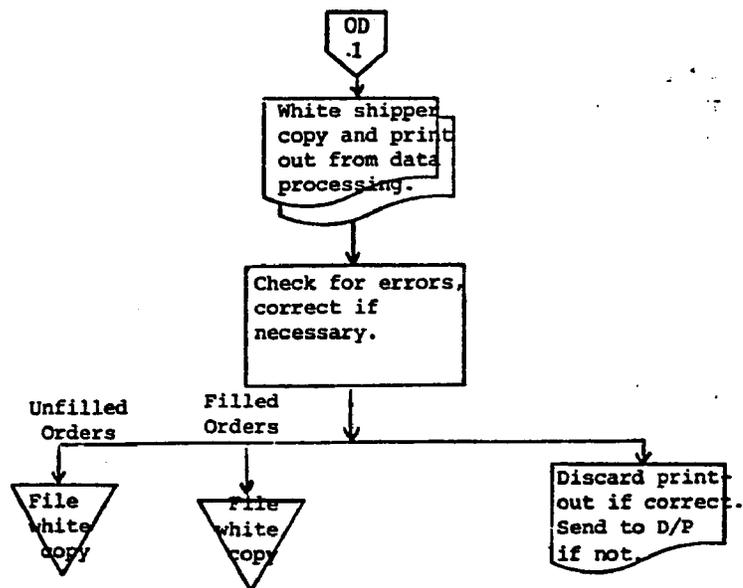
Figure 5.   Error Check on Rush Orders
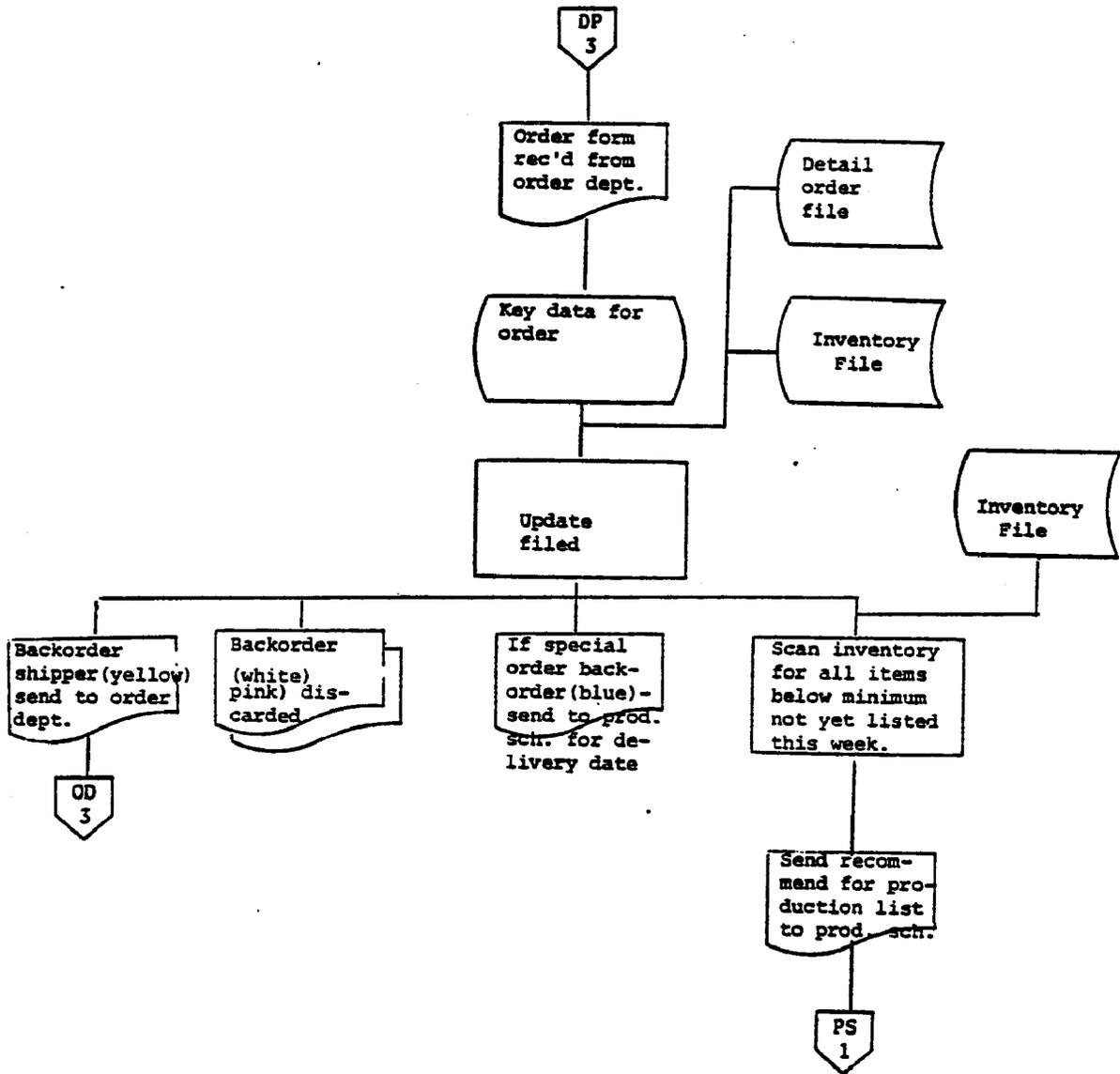
Figure 6. Keying of Data from Order Form

file is the addition of all orders received to those orders previously received but not yet shipped. The inventory file is accessed and the amount of goods available for filling customer orders updated to reflect the allocation of inventory to orders on a first-come-first-served basis. The only exceptions to the first-come-first-served rule are the rush orders; these orders are processed prior to the regular orders on any given day so that the inventory records will reflect the inventory allocations that have already been made (manually) on the in-stock-list for the rush orders.

For each order, a shipper is generated each item of an order entered as one line on the shipper. For each item the total amount of the product ordered, the amount of the order previously shipped (if any), the amount to be shipped (if any), and the location in the warehouse of any stock that is to be shipped is entered on the item line. If any item on the order has a positive amount to be shipped the generated shipper is sent to the warehouse for use in order picking. If no items on the order have a positive shipping quantity (complete backorder), the white and pink portions of the four part shipper are discarded and the yellow portion is sent to the order department for filing to maintain a record of shipments and amount of order outstanding (Figure 7).
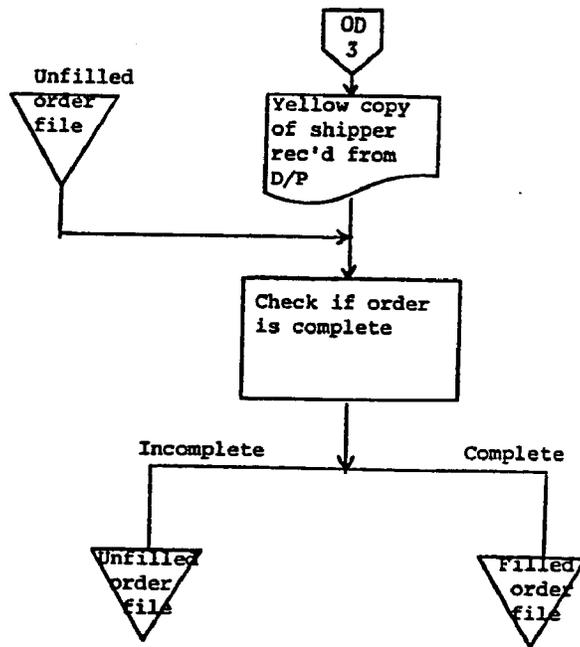
Figure 7.   Check for Order Completion

The blue copy of the shipper is, if the order requires it, sent to the production scheduling department for an estimate of shipping date; the estimate being written on this blue copy of the shipper and sent to the customer.

During the processing of the orders received during the day, a listing of those items which have fallen below their reorder points because of allocation of inventory to customer orders is generated. Inventory records are updated to reflect this recommendation of production which has not yet been scheduled. This listing is called the recommended for production list and is printed on a daily basis in addendum form and at the beginning of a scheduling period on the first day of a scheduling period. This list is used by the production scheduling department to generate production schedules for the products required.

Generation of Production Schedule, Job Tickets and Release of Job Tickets to Floor

Upon receipt of a complete recommended for production list from data processing at the start of a scheduling period (Figure 8) the production scheduling department will divide the recommended list into product groups. For this firm, there are four major product lines; two of the lines are scheduled by one method and the other two lines, which will be used in the study of

PS 1

Recommended for production list rec'd from D/P

List for block

List for press strip

List for rolled strip

List for disk brake

Determine schedule from list - pool by print number

Preprocess list- sort out salvage items and prod. items

Preprocess list- sort out salvage items and prod. items

Determine sche- dule - pool by common part #

Rec. for prod. list- discard end of wk.

Rec. for prod. list- discard end of wk.

Rec. for prod. list- discard end of wk.

Rec. for prod. list- discard end of wk.

Items to be scheduled

Prod. items list

Prod. items list

Items to be scheduled

List of salvage items

List of salvage items

PS 5

PS 5

Items to be sch. and prod. item list to D/P

DP 4

Figure 8. Generation of List of Items to be Scheduled and Salvaged

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the effect of increasing batch sizes are scheduled in a slightly different manner.

The two product lines are scheduled by sorting the recommended list by dimensional and/or material characteristics which, when grouped, increase operational efficiency in the first operation (which is common to all products) due to the sequence dependance of set-up times of the manufacturing operations. The other two product lines, which will be the basic data in later analysis, are scheduled by grouping by common characteristics after a pre-processing (sorting) step is completed. This pre-processing step identifies those orders which have small production requirements, usually these orders are for products for which inventory is not carried. The items with small production requirements are checked for similarity to items which are currently in inventory; if the ordered items are sufficiently similar to one which is in stock, the recommended item is made by reworking (salvaging) the item in inventory in order to avoid much of the manufacturing that would be required to produce the recommended item from raw materials. Large batch or unsalvageable items are placed on the items to be scheduled list.

The list of salvage items is used to gener te salvage and job tickets (Figure 9). These tickets
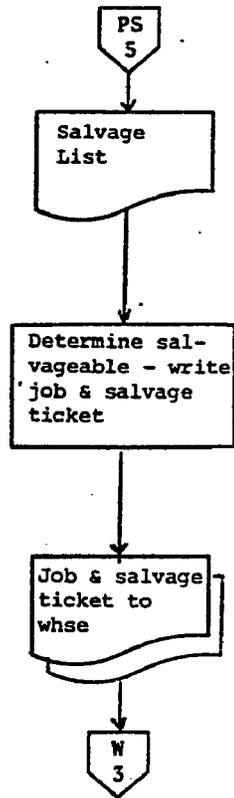
Figure 9.   Generation of Job and Salvage Tickets

are sent to the warehouse (Figure 10) and used to pull the goods which are to be reworked (salvaged) in the warehouse, the job ticket and the goods being sent to the production floor (Figure 15) and the salvage ticket being sent to data processing for use in file updating, (Figure 11) to reflect the change in status from finished goods to work in process.

The list of items to be scheduled is sent to data processing (Figure 12) for use in file maintenance and job ticket generation. The manufacturing in process file is updated to reflect the addition of the items scheduled to the manufacturing in process. At this time, raw materials are allocated to the items scheduled and the inventory position of the raw materials is checked and any requisite orders placed. Job tickets, inventory control cards and material control cards are generated at this time. The job ticket serves to identify the job through the required processing sequence. The material control card is used to provide authorization for drawing the raw materials to manufacture the item and is used in scrap control. The inventory control card is used at the completion of the manufacturing of the item to acknowledge the receipt of items into finished goods inventory. When the item is received from manufacturing, a count of the item is taken and recorded on the cards, the cards serving as input for

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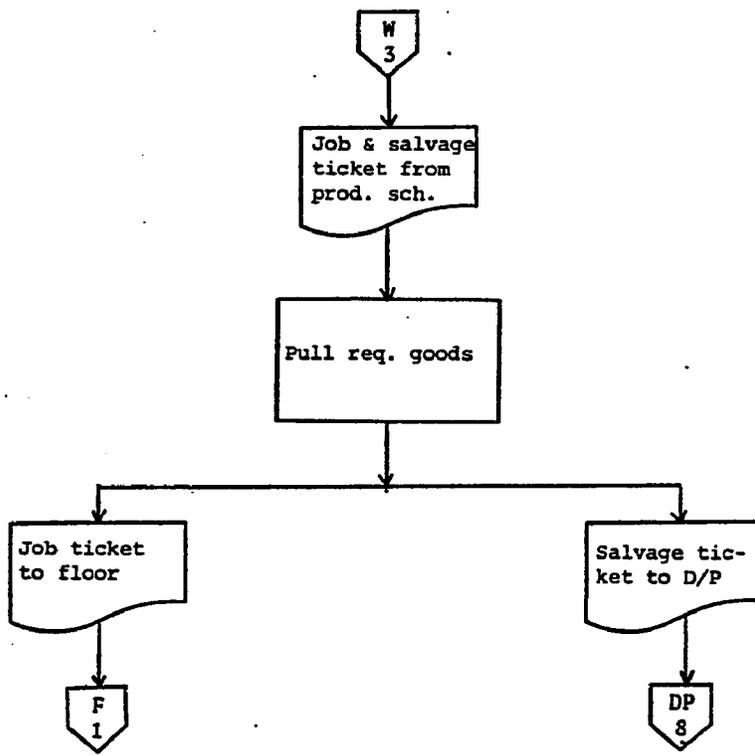
Figure 10. Processing of Job and Salvage Tickets
and Pulling of Goods in Warehouse
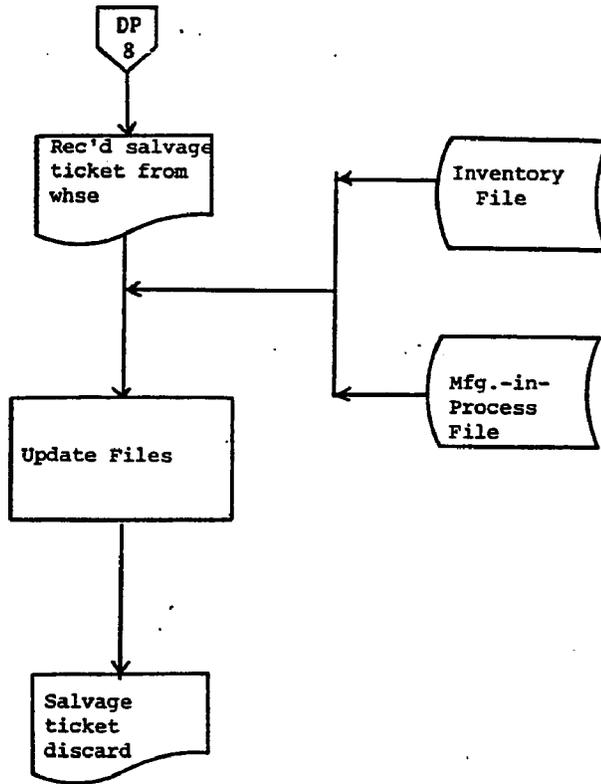
Figure 11. Receipt of Salvage Ticket in Data Processing
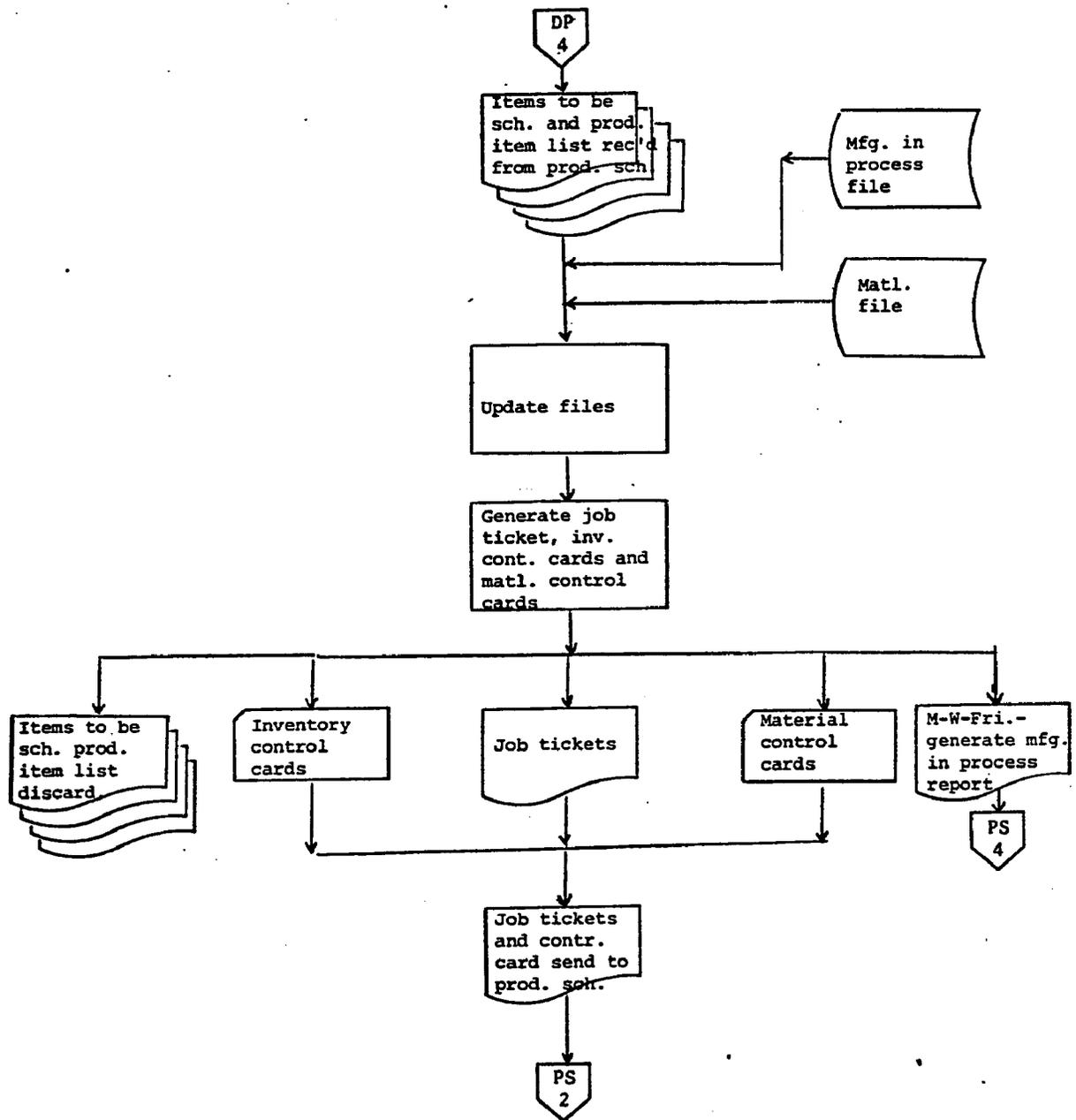
Figure 12. Generation of Job Tickets and Manufacturing-In-Process Report

the updating of the inventory file.

Upon receipt of the job tickets and inventory and material control cards (Figure 13) the production scheduling department sorts the tickets by product line. For the product lines, the job tickets and control cards are checked for errors and assembled. For the two lines which will be used for the study, the original equipment (O/E) requirements are added to the schedule (Figure 14). The scheduling of the original equipment orders are used in production scheduling; the orders for original equipment are known in advance and additional O/E can be scheduled to balance periods of low production.

Processing of Job on Manufacturing Floor

The assembled job ticket and control card packets are delivered to the manufacturing floor (Figure 15). The material which is required for the job is requisitioned; the authorization for this requisition is the exchange of the material control card for the raw materials. The material control card is then sent to data processing (Figure 16) where it is used to update the manufacturing in process file to indicate that the scheduled manufacturing of the particular item has begun.

The raw material is formed into its rough shape. At this point in the process the semi-finished goods

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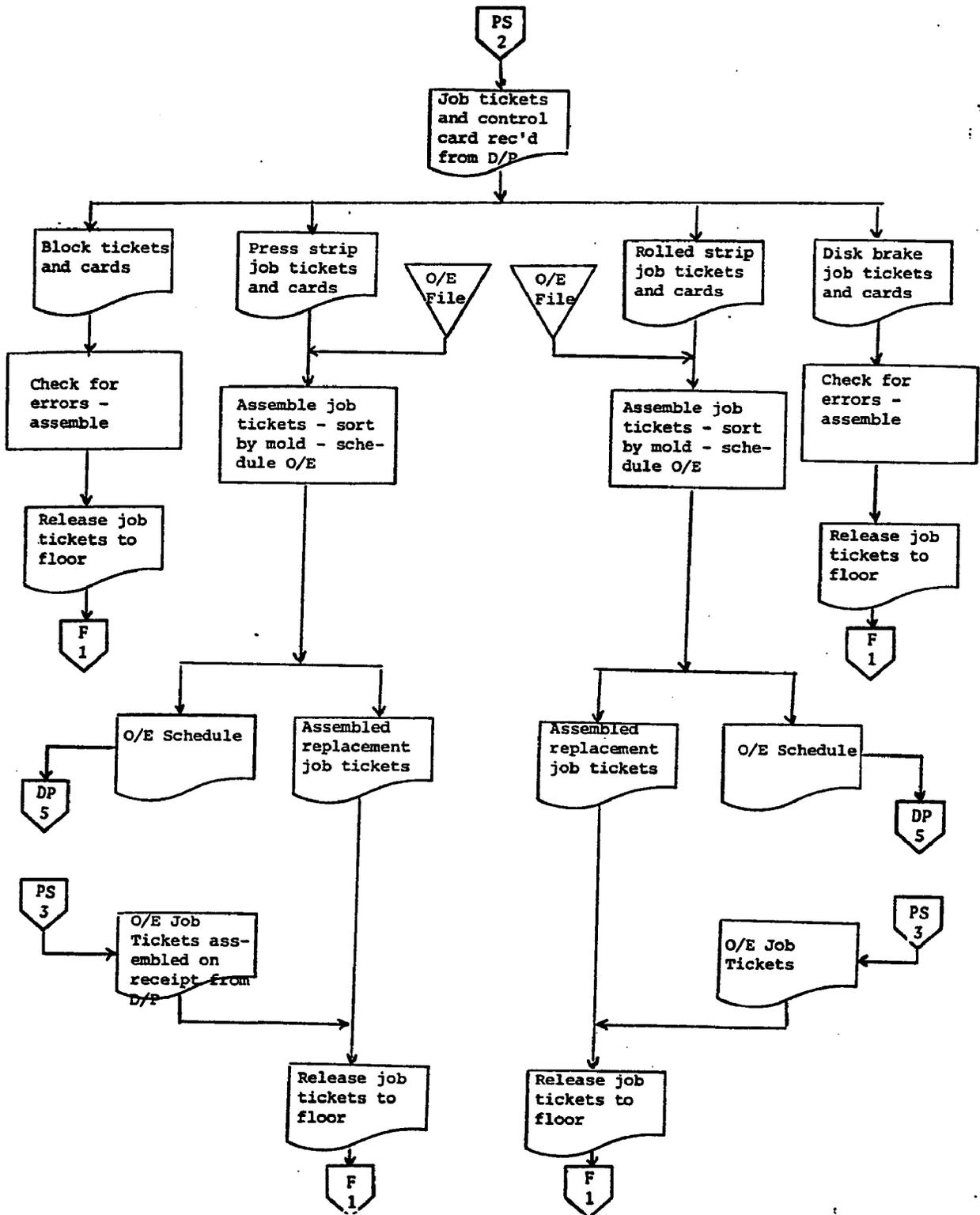
Figure 13. Generation of Schedule and Preparation of Job
Tickets

49
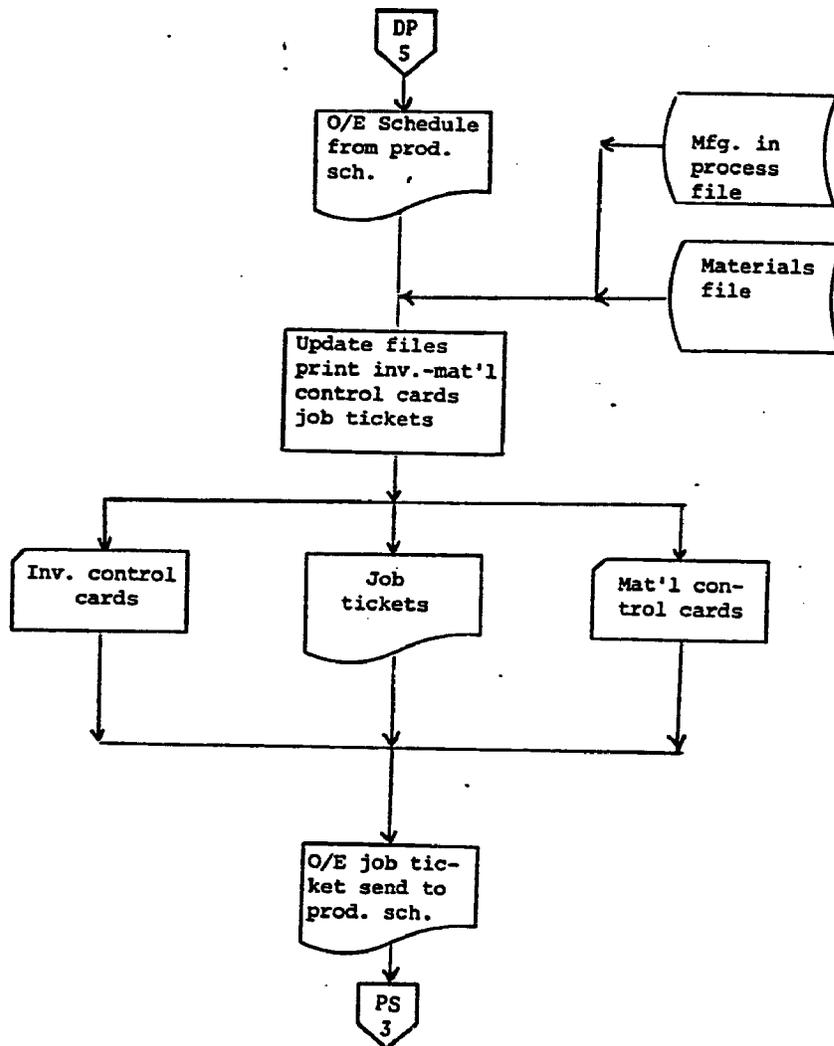
Figure 14. Generation of Job Tickets for Original Equipment
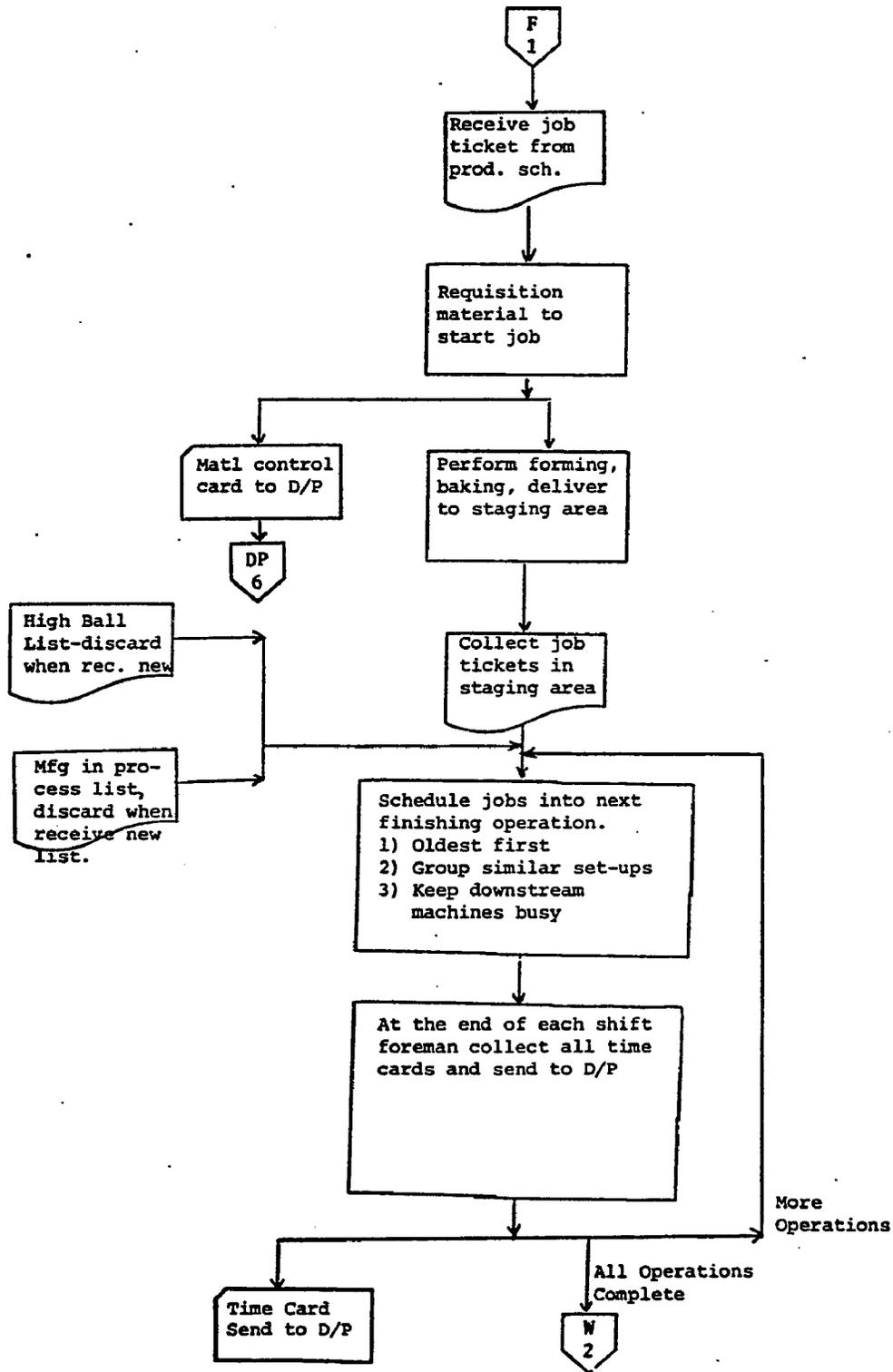
Figure 15. Production of Item on Floor
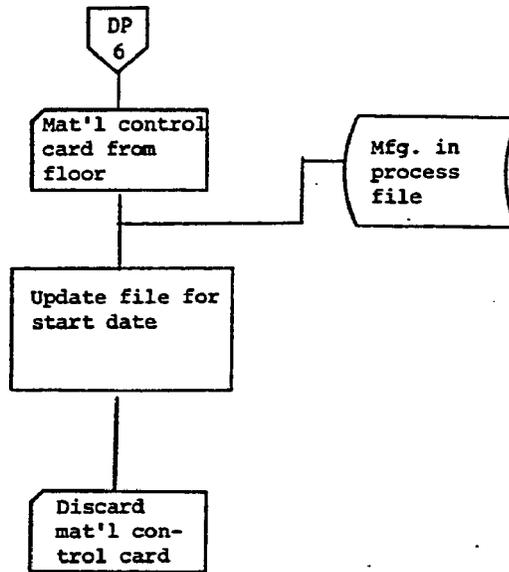
Figure 16. Update of Manufacturing-In-Process File

are placed in a staging area and the job tickets collected. The job tickets are then manually sorted to determine the sequence in which the jobs will enter the finishing area. The high ball list which is generated by production scheduling via comparison of the manufacturing in process and the backorder list (Figure 17) a list of items falling behind schedule and the manufacturing in process list, a list of all ongoing manufacturing, are used by the foreperson along with his knowledge of similarity in job setups to determine the job processing sequence. Additional considerations in the determination of the job processing sequence are efforts to schedule the oldest jobs first and keep the downstream (later finishing operation) machines busy; this is done to increase shop efficiency and throughput.

A queue of job builds in front of each type of machine in the finishing area. A sequencing decision process that is similar to the one described above for entry into the finishing area is used in determining which job is run next on a particular machine.

At the end of each shift, the foreman collects all time cards and sends them to data processing for labor reporting and updating of the manufacturing in process file (Figure 18).

At the completion of all manufacturing operations,

Figure 18. Receipt of Time Cards

Figure 17. Generation of High Ball
List

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the finished parts are sent to the warehouse

Receipt of Finished Goods at Warehouse and Shipping of Outstanding Orders

The warehouse receives completed parts and inventories them (see Figure 19). At this point in time, the job ticket has fulfilled its purpose and is discarded and a count of the number of parts received is made and this number is written onto the inventory control card and sent to data processing.

Data processing receives the inventory control card from the warehouse (Figure 20) and keys in the physical count data. This data is used to update the inventory file and the manufacturing in process file; the former reflecting the addition to inventory, and the latter, the reduction in the manufacturing in process. The order file is then checked to determine if any outstanding orders can be filled; if so, a shipping document is generated, one portion of which is sent to the order department as notice that the order is being filled, and the other three sections of the shipper are sent to the warehouse.

In the warehouse (Figure 21), the goods required to fill the order are picked and shipped and the yellow copy of the shipper is sent to the order department where it is screened for any credit adjustments or other special processing (see Figure 22) and sent to data processing.

```
        ┌─────┐
        │  W  │
        │  2  │
        └──┬──┘
     ┌─────┴──────────┐
     │ Completed parts│
     │ delivered to   │
     │ finished goods │
     │ and inventoried│
     └────────┬───────┘
      ┌───────┴────────────────┐
┌─────┴──────┐          ┌───────┴──────┐
│ Inventory  │          │ Job ticket   │
│ control card│         │ discarded    │
│ to D/P     │          │              │
└─────┬──────┘          └──────────────┘
   ┌──┴──┐
   │ DP  │
   │  7  │
   └─────┘
```
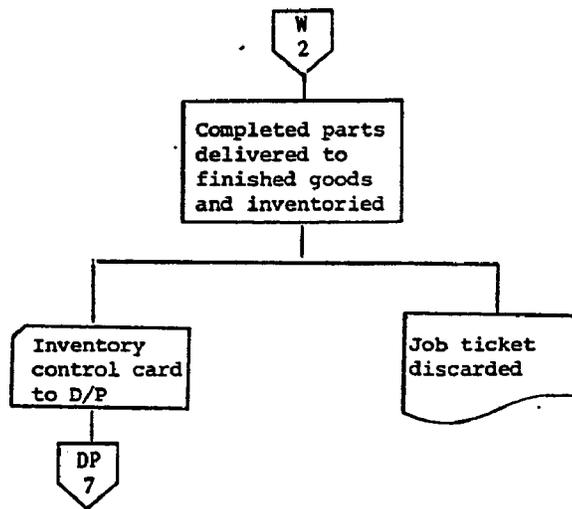
Figure 19.   Receipt of Finished Goods in Warehouse
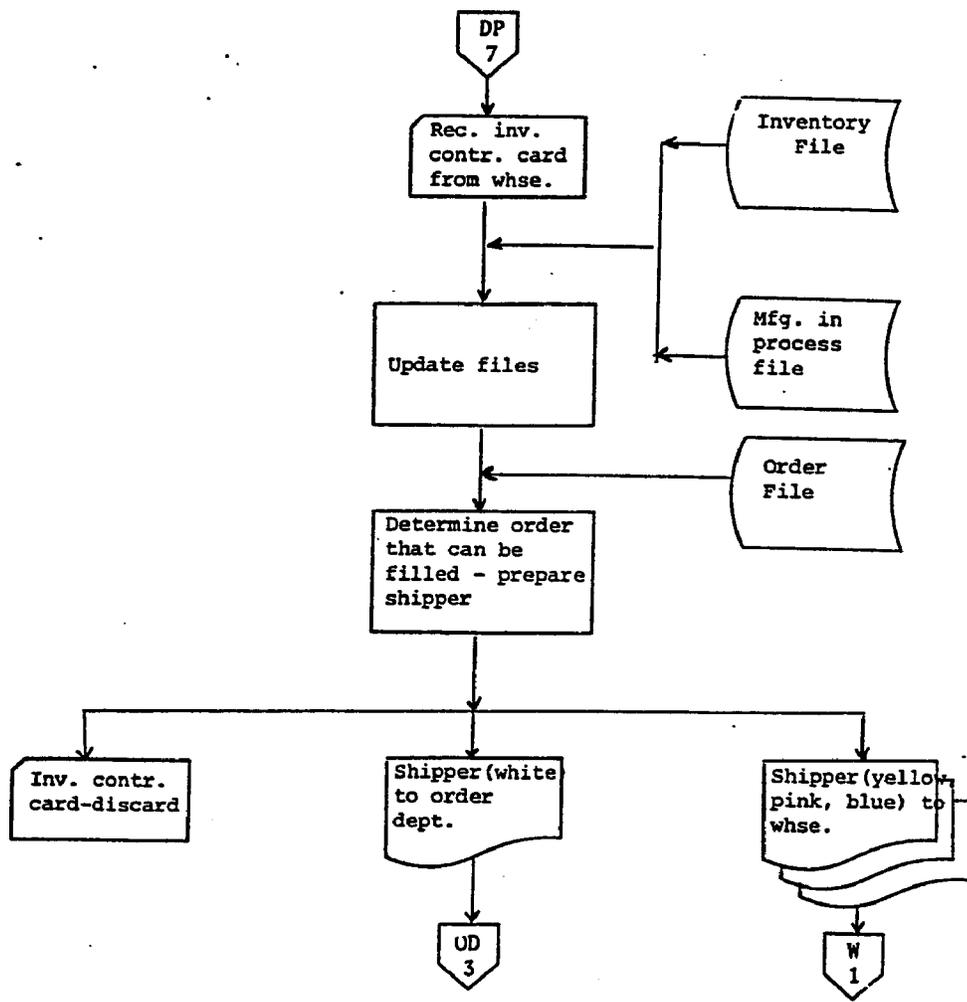
Figure 20. Receipt of Inventory Control Card and Shipper Generation
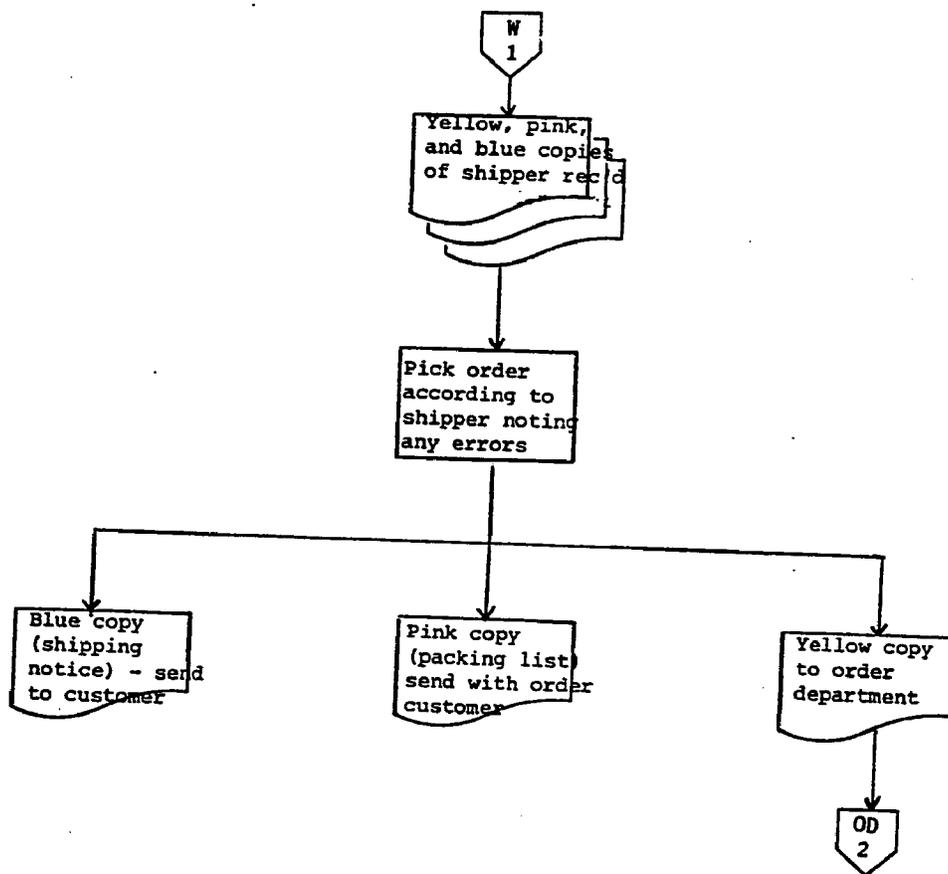
Figure 21. Order Picking in Warehouse

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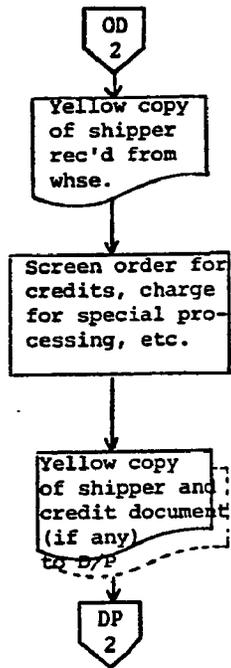
Figure 22. Screening for Credits

Upon receipt of the notice of shipment from the order department (see Figure 23) the data on the shipment is keyed and the inventory and order files updated. At this time an invoice is generated and shipped to the customer. The yellow copy of the shipper is then sent to the order department (see Figure 7) for filing.
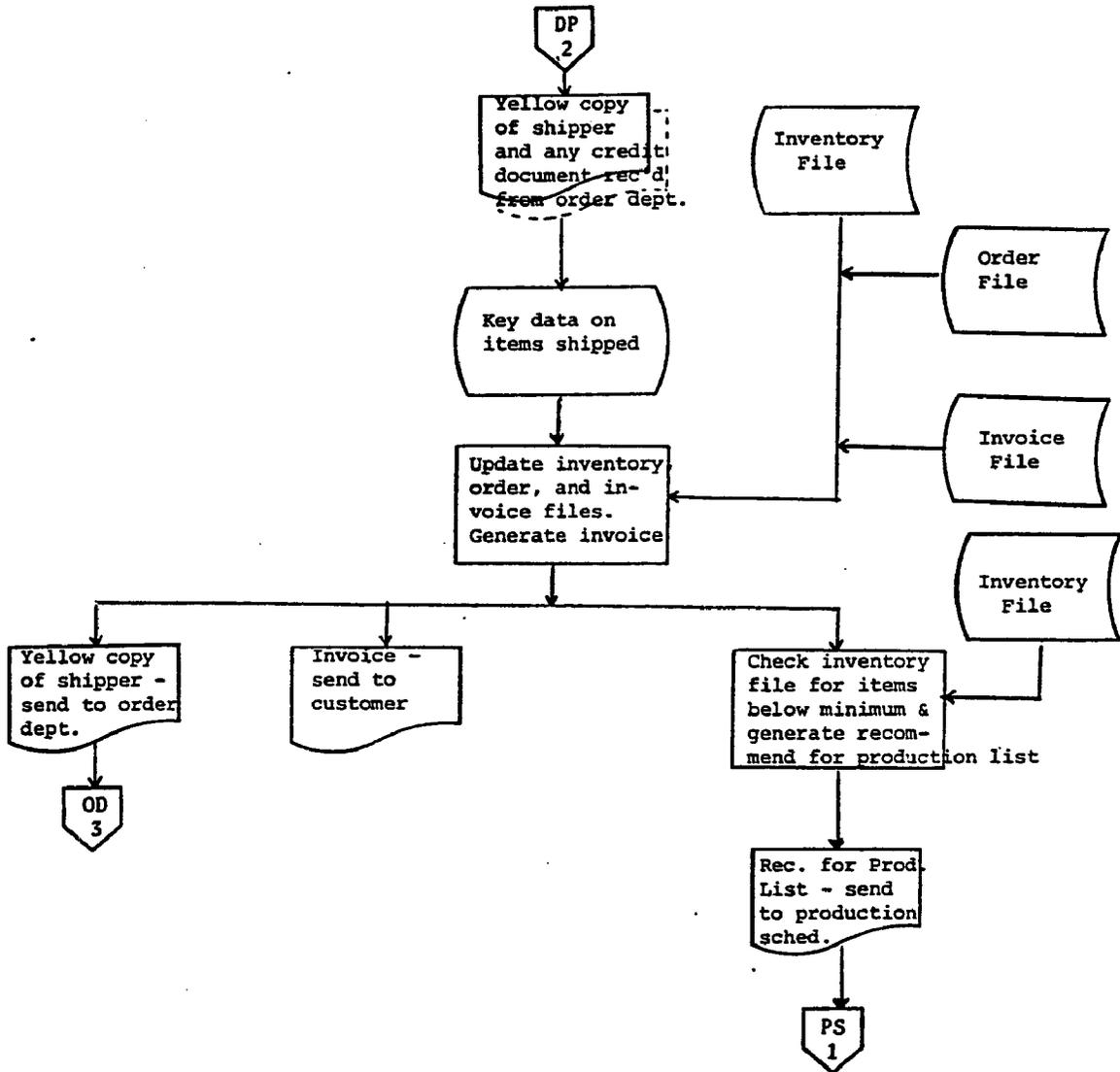
Figure 23. Update of Files to Reflect Order Shipment

CHAPTER 3 - METHOD OF SOLUTION

3.1 Investigation and Selection of Solution Methodology

The investigation of this type of inventory problem began with a detailed study of the existing order entry/production-inventory to gain a thorough understanding of the system and additional insight into the problem. During this study, the system flowchart of the order entry/production-inventory system presented in the preceding chapter was constructed and the opinions of operating and managerial personnel concerning system problems and possible solutions were solicited. All personnel indicated that the small batches of product which were going through manufacturing were the source of much of the planning, scheduling, and control problems on the manufacturing floor.

Several strategies were suggested for improving the operational efficiency of the manufacturing facility; they were:

1. Abandon the small and/or infrequent demand business, that is delete, the products in the later stages of product life from the product line,

2. Attempt to get customers to purchase in larger quantities by

    a. Requiring all orders to be over a minimum amount, or

b. Revising the pricing structure to a fixed
   (set-up) charge per order and a per piece
   price,

3. Introduce a decision rule which would require
   all manufacturing lot sizes to be above some
   minimum amount

   a. By delaying production of the product
      until sufficient orders have been
      received to justify the lot size, or

   b. By producing larger batches of items as
      they are first needed and storing the
      excess and using it when additional orders
      for the item are received.

4. Make no changes and absorb the costs which
   result.

The first two alternatives affect the customer
directly and may present difficulties in implementation.
A reduction in the product line offered may reduce
sales as customers may prefer to deal with one supplier
who offers a complete line rather than with several
suppliers. Customers may change suppliers if one of
the suppliers enforces a minimum order size and the
other suppliers do not even when this change will
require the payment of higher prices as the supplier
with the minimum order size forces the customer to hold
the inventory while the other suppliers do not. A

revision of the price structure may also encounter customer resistance as it may also force the customer to carry his own inventory.

The introduction of a minimum manufacturing lot size decision rule, however, is internal to the firm, that is, the customers will not be affected as directly. The analysis of the effect of this decision rule can be accomplished through the use of simulation. The use of simulation will allow the model to reflect all of the major interactions of the real system without the necessity of making a large number of simplifying assumptions in order to obtain mathematically neat and rigorous results; rigorous mathematical results may not be achievable using a model which incorporates all of the complexities in the system under study. Simulation will allow for the use of a multi-criteria objective function rather than the single criterion of performance that most mathematical models allow. Through the use of a multi-criteria objective function, the analyst can perceive and evaluate the effect of this inventory policy in more of a global fashion.

The objective of this simulation will be to generate data from which an analysis of the transient and long term effects of the introduction of a minimum manufacturing batch size rule using data from a real

world industrial firm. The effect of the rule will be measured in terms of the changes that occur in inventory level, customer service, and number of setups over time. The procedure that will be used in this study will be to build a simulation model of the order entry/production-inventory system of the firm and simulate the behavior of the system under various levels of minimum batch size (e.g. 0, 50, 100, ...) in order to determine if a minimum batch size rule has economic value to the firm.

The simulation model which will be built will incorporate as much of the real world complexities as possible. The handling of rush orders will not be incorporated into the model as the data which is necessary for identification of rush orders in the order stream does not exist. The data needed to determine which finished goods could be salvaged was also not accessible and this aspect of the system was also not incorporated into the model. The model will produce raw data about the system's behavior under the decision rules and any load or workforce leveling that occurs is external to the model.

3.2 Overview of Simulation Model Language

The simulation model used in the analysis of this problem uses the basic structure of the Generalized Algorithm for Simulation Programming (GASP). The system modelled is the order entry/production-inventory of the firm supplying the data to be analyzed, as described above. GASP is a FORTRAN based simulation language developed by Pritsker and Kiviat (15) to aid in the programming description of the models of systems to be simulated.

GASP is an event-oriented, discrete simulation language consisting of a set of FORTRAN subroutines to which the user adds in order to build a simulation model of the system that he/she desires to study. It is designed to provide seven functional capabilities required in every simulation:

1. Event control,
2. System state initialization,
3. Program monitoring and event reporting,
4. Statistical computations and report generation,
5. Information storage and retrieval,
6. System performance data collection, and
7. Random variable generation.

The first four functional capabilities are control oriented, when the simulation is engaged in the execution

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of one of these functions, it is not engaged in any other. The last three are utility functions; they provide some of the computational and/or data processing functions necessary during the simulation experiment.

Event control is achieved through the use of a timing mechanism which provides for the orderly (in simulated time) processing of the events which occur during a simulation experiment. An event is an identifiable point in time when a particular activity which occurs in the simulation begins or ends, e.g. the point in time when a product is delivered to the ware-house from manufacturing is the end of the manufacturing process--this point in time is also the beginning of the storage time for the product. The orderly process-ing of the simulated events is accomplished through the establishment of a GASP file (discussed in detail below) whose records consist of at least two fields; the first field is the time at which the event occurs and the second field is used to describe the type of event which occurs at the particular point in time. The file is keyed on the first field, arranged in ascending key sequence and is accessed sequentially. By accessing this file and processing the event which is coded in its first record whenever an event is to be processed (i.e. when the processing of the preceding event is completed) and by placing additional entries in the

file and preserving the sequence of event times, assures the logical and orderly processing of events during the simulation.

The events which are controlled in the above manner are either simulated events or program monitoring events. The simulated events are those whose occurrence is a representation of the events that may occur in the modelled system, and program monitoring events are those used to provide information on the logic being exercised in the computer model, that is, on the operation of the model rather than the system being modelled and are used in program debugging and testing. The model-builder supplies the initial events and parameter values for the simulation via data cards and/or data files. The processing of these events will, in general, generate succeeding events; e.g. an event which signifies the release of manufacturing orders to the floor may generate the completion of manufacturing events for each item scheduled and the next manufacturing order release period. This process of generating succeeding events during processing continues throughout the simulation experiment.

Statistical computation and report generation are accomplished via execution of user written or GASP supplied subroutines. These routines produce tabular and/or graphical reports on the data collected during

the simulation experiment. The user may choose to
generate these reports on an intermediate and/or final
(end of simulation) basis. The data collected and output
constitutes the data set used in problem analysis.

The typical GASP simulation program is shown in
Figure 24. The programmer must supply a main program
and at least three types of subroutines, event control,
event description, and report generation subroutines;
additional types of subroutines may be required
depending upon the system modelled and the type of data
storage used. The GASP simulation language supplies
subroutines which provide the timing mechanism and
generation of a final summary report (which is
augmented by the user generated reports) and utility
subroutines which provide for information storage and
retrieval in the GASP files, provide for initialization
of requisite GASP parameters, error reporting, and
collection of statistics.

Logic

The basic logic of the simulation program models
the order entry/production-inventory system described
in Chapter two and is shown in Figure 25. Program
execution begins with the main program which is used
to initialize all of the non-GASP parameters, to call
subroutine OTPUT to generate an initial condition
summary report as an echo check on the parameters read
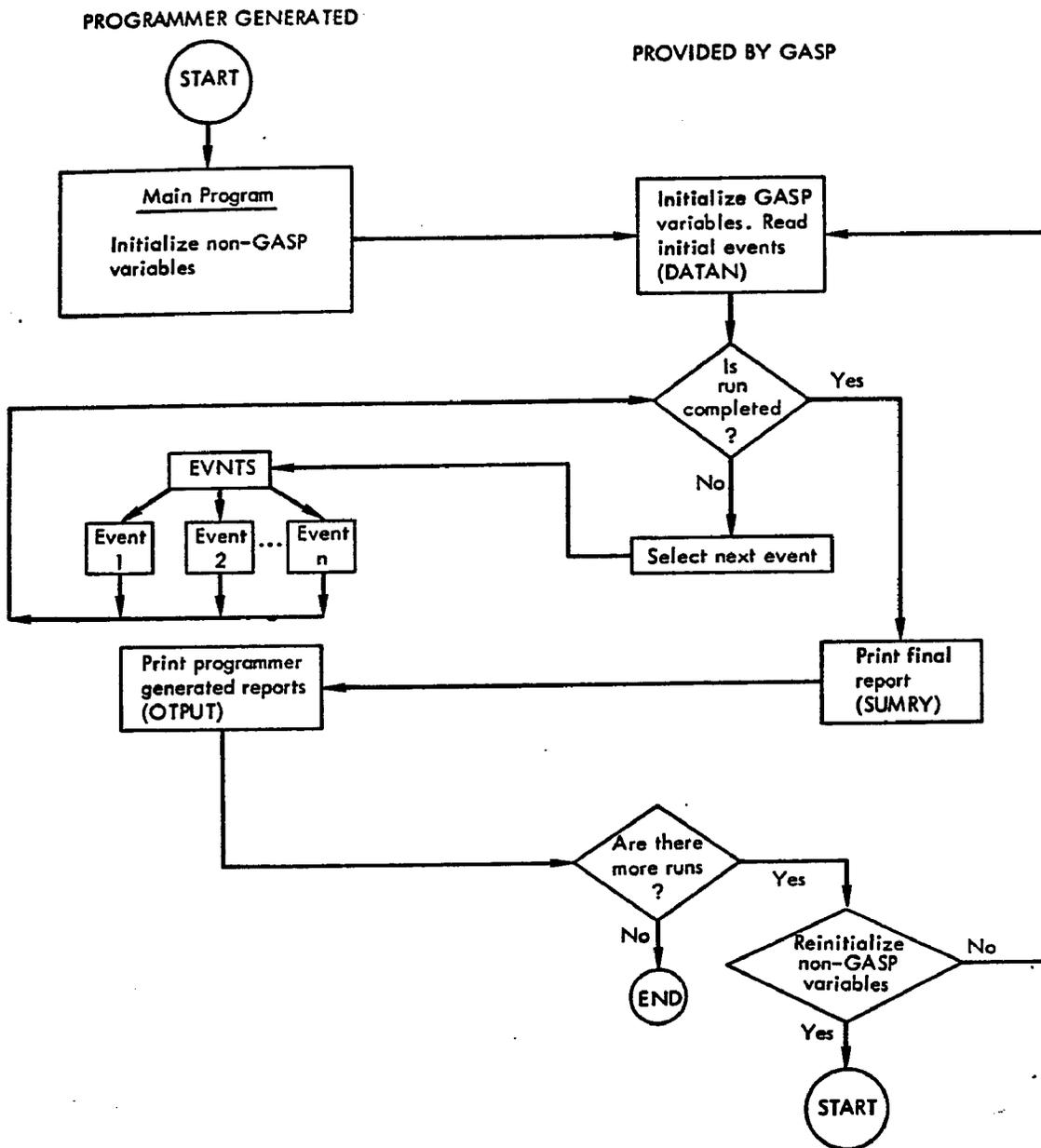
Figure 24. A Typical GASP Program
From (15, pg. 19)
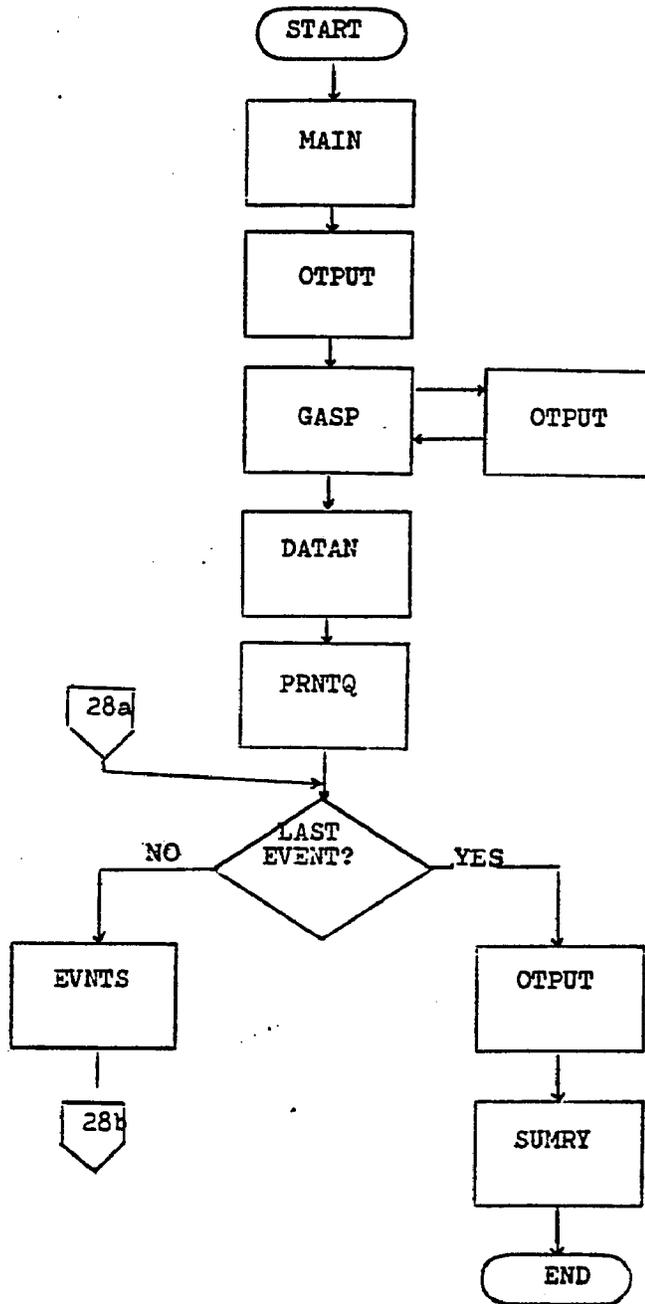
Figure 25. Overview of Simulation Program Logic

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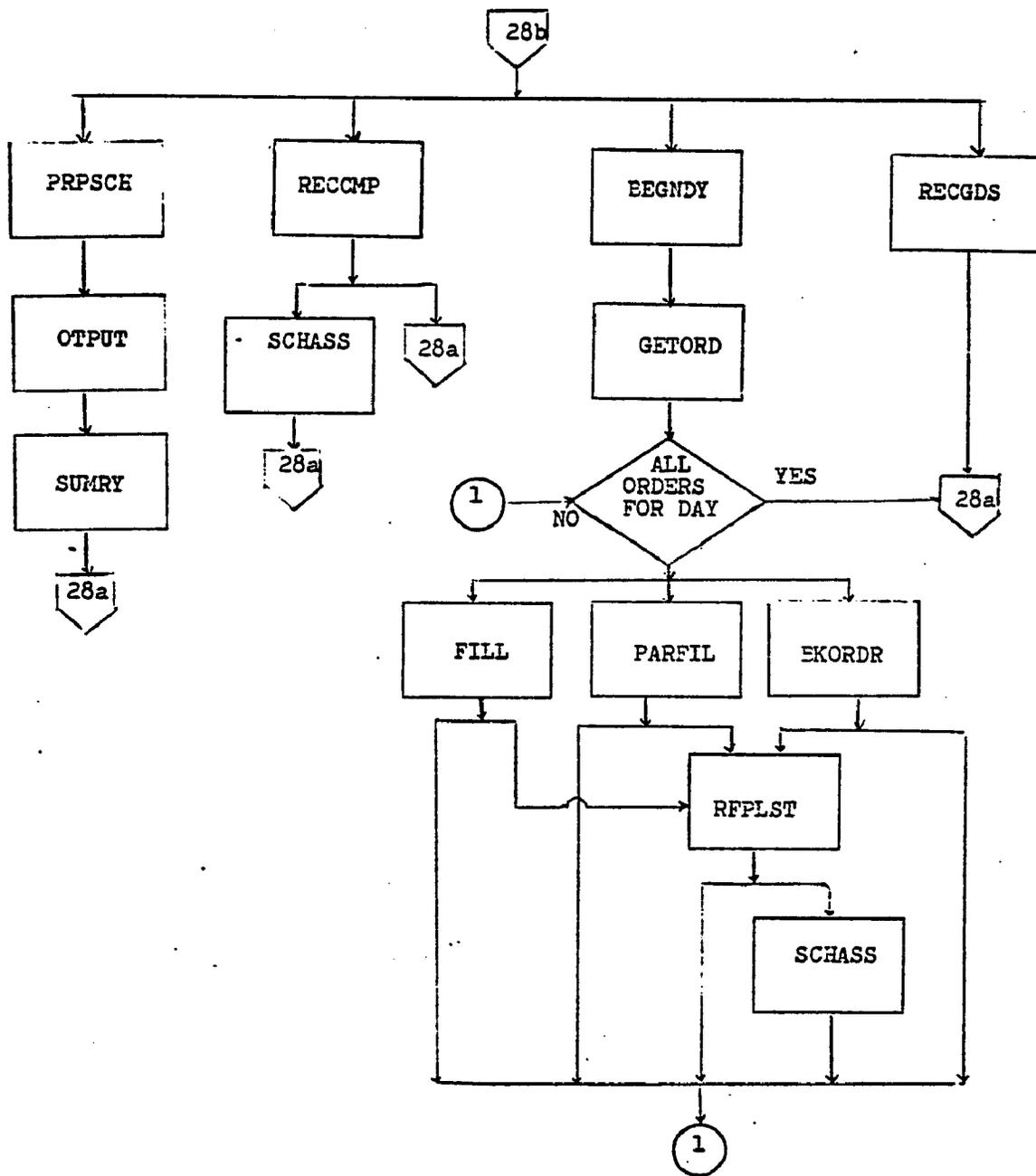
Figure 25 (Continued)

in the initial values of the GASP parameters; this subroutine sets up the storage array NSET so that all GASP files may be stored, and places the user-supplied initial events in the GASP file events. Control is returned to GASP after completion of the initialization task, and subroutine PRNTQ is called to print out the GASP files as an echo check. The GASP subroutine then access the first event from the events file and checks the time of event occurrence with the ending time for the simulation. If the event time is greater than the simulation ending time, the end of the simulation has been reached and the final summary is printed using subroutines OTPUT and SUMRY. If the event time is less than the simulation ending time, one of the four sets of subroutines which constitute the processing of the four types of events that can occur during simulation experiments using this model is called the four events that can occur during this simulation are: beginning of a day, end of a scheduling period, receipt of components and receipt of finished goods. By calling subroutine EVNTS which uses the second field of the events file record (event code) to call the correct set of subroutines.

If the event is the beginning of a new day, subroutine BEGNDY is called to collect time integrated

statistics on inventory levels and subroutine GETORD is
called to get (from file) the orders for the simulated
day and determine if the in-stock inventory level for
the ordered item is: sufficient to fill the order from
stock (subroutine FILL), insufficient to fill the order
but some of the item is available to be used to
partially fill the order (subroutine PARFIL) or zero,
indicating that the item must be backordered (subroutine
BKORDR). Subroutines FILL, PARFIL, and BKORDR collect
statistics on the number and size of orders that are
processed by each of the routines. Each of the three
routines check the amount of inventory (both finished
goods and manufacturing-in-process) against the product's
reorder point and determine if additional finished goods
are necessary; if not, control returns to subroutine
GETORD for processing of additional orders; if so,
subroutine RFPLST is called to determine if sufficient
components are available to assemble all or part of the
order and check the amount of components available
against their reorder points to determine if a manu-
facturing order for the component should be generated,
if a manufacturing order is necessary, the component is
placed on the recommended for production list which is
used in scheduling the plant at the end of each
scheduling period; if not, control returns to subroutine
GETORD.

If the event is the end of scheduling period event, the items on the recommended for production list are released onto the manufacturing floor and the receipt of component events, which indicate the completion of manufacturing of the item, are generated statistics on the number and size of job tickets are collected at this time and subroutines OTPUT and SUMRY are called to print a summary of the activity which occurred during the scheduling period.

If the event is indicative of the completion of the manufacturing operations on a component, that is, the receipt of the goods into component inventory, subroutine RECCMP is called to collect statistics relating to the receipt of this component into component inventory. If this particular component is the last one for which a receipt is necessary prior to beginning assembly of a finished good, subroutine SCHASS is called to schedule the completion of assembly event.

If the event is a completion of assembly event, subroutine RECGDS is called to update finished goods inventory, if necessary, and collect statistics on the completion of service on orders.

Upon completion of the processing, file updating and collection of statistics for the events, control is transferred back to subroutine GASP which selects the next event and determines the relationship of the

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event time to the ending time of the simulation. If the ending time has been reached or exceeded, subroutines OTPUT and SUMRY are called to generate final summary reports for the simulation run, otherwise event processing continues.

Information Storage and Retrieval

The key to successful simulation is the ability to access and modify information during the simulation experiment. The GASP simulation language provides for information storage and retrieval by maintaining files of information within a large two-dimensional array in memory. Each column is used to store one entry, that is, one record of a file; the rows positions within the column are used to store the fields of the record. Using this scheme it is possible to access a record through knowledge of the column in which it is located and access to a particular field may be obtained through knowledge of the row and column of the desired field.

The linking of the entries in the GASP files or (the columns of the filing array) to facilitate the processing of the entries in a file is achieved through the addition of two pointers to each record in the file. These pointers are the columns in the filing array where the preceding and succeeding file entries are stored. The presence of these pointer fields allows the processing of the entire file in a forward direction by locating the first entry and tracing through the records (columns) using the successor file entry (column) pointer or in a backward direction by locating the last file entry and tracing through the records

using the predecessor file entry pointer. The array columns containing the first and last entries of the files must, of course, be stored separately and their predecessor and successor fields are coded in a manner which indicates that the record has no predecessor or successor in the file.

A record's position in the file is determined by the value of its key field and ranking procedure. The ranking procedures for a file are either high values first or low values first and any field may be designated as the key field. Additions to a file are accomplished by placing the record in an empty column of the filing array and adjusting the pointer field of its predecessor record to point to the column in the array occupied by the additional record and the pointer field of its succeeding record to point back to the column of the newly added record. Additions and deletions to the files were handled by the GASP routines FILEM, RMOVE, and SET. FILEM is used to add an entry to a file; RMOVE is used to delete a particular file entry and subroutine SET is used to update the pointers.

The location of a particular record is obtained by calling the GASP subroutine FIND. This subroutine searches the file sequentially until a record which meets the search criteria (e.g. a particular value for

a particular field, the first negative value for a field etc.) or the end of the file is found, and returns the column of the filing array of the desired record or a zero to indicate no record in the file met the search criteria. For this simulation it was often necessary to locate records having two fields matching particular value, a user written subroutine called FIND2 was written to sequentially access a GASP file and returned the column of the filing array of the first record that had fields which had the specified values or a zero if no record having fields matching the desired values was found.

This filing scheme works well for most simulations in that access is rapid and the "housekeeping" routines are supplied. For this simulation study, however, the volume of data necessary for the inventory, bill of materials, and where used files was large and could not be accommodated in memory. The only solution to this problem was to store most of this data on a peripheral device and bring into core only the required record. The requisite files could be set up and accessed by either a FORTRAN direct access file which must be filed sequentially and accessed by a key which must be the record's relative position in the file, or a COBOL direct access file where the filing key may be any field of the record. The major files that were required by the simulation were in the firm's data base,

and were keyed on a five digit part number code.
Although not every record on the files would be needed
during the simulation, the portion of the files relat-
ing to the product lines under study contained over
thirty thousand (30,000) records.

Use of a FORTRAN direct access file was eliminated
from consideration because it would required either very
large disk files with very low density if the part
number code was used as the key or a reasonably
sophisticated software package which would increase the
density of the file by using an algorithm to relate
part number code to relative position in the file while
eliminating duplication (same relative location for
two different, part number codes).

The alternative, the use of the COBOL language file
utilities was accomplished in a relatively straight-
forward manner on the IBM equipment used for this study
(the ease with which this concept can be transferred to
other manufacturer's equipment is unknown to the author
at this time). The basic logic was to call a COBOL
subroutine from the FORTRAN simulation passing as
arguments to the COBOL routine codes indicating the file
that was to be accessed, the action to be taken with
the record (either a read or a write action was
permitted), the value of the key (part number code) of

the record in the file desired, whether a search for additional records with the same key should be sought, a return code indicates the status of the seek (successful, unsuccessful), and a string of fields used to either return values found in the file to the FORTRAN program (if the read action was specified) or transfer values to the COBOL subroutine to be written onto the file (if the write action was specified).

3.3 Input Specifications for Simulation Model

Three types of input data are required for successful execution of the order entry/production-inventory system simulation program. External (disk) files of the order history information, and the bill of materials, inverted bill of materials and inventory files for the product lines under study must be set up prior to execution for use during the simulation experiments. The order history file is a data file read sequentially while the other three files are accessed randomly (via the COBOL subroutines) to obtain particular records during execution. GASP files are required and are built in core and used during program execution.

Disk File Specifications

The order history file contains all the orders that will be processed during the simulation. The information on this file is obtained from the order history file of the firm's data base. A COBOL program was written to pull from the data base order history file the orders for the product line(s) to be studied during the simulation experiment, and put them in the proper format.

Each record of the order history file contains eleven (11) fields which are shown in Table 1. All

Table 1. Field Specifications of Order History File

Field	Information Contained	Size of Field	Data Type	Number of Decimal Places	Justification	Variable Name for Field
1	Market code of item ordered	3	Numeric	∅	Right	MKTCOD
2	Product code of item ordered	2	Numeric	∅	Right	PRDCD
3	None - spacing	2	--	--	--	--
4	Time order placed (in simulated time)	6	Numeric	2	Right	TIME
5	Customer code - where to bill Part 1	5	Alpha-numeric	--	Right	CUST 1
6	Customer code - where to bill Part 2	4	Alpha-numeric	--	Right	CUST 2
7	Number code of item ordered	5	Numeric	∅	Right	PNCDFG
8	Size of order (in # sets of item)	8	Numeric	∅	Right	QUANT
9	Total price of order ($)	1∅	Numeric	2	Right	AMT
1∅	Code of warehouse receiving order	1	Numeric	∅	Right	WHSE
11	Order number	6	Numeric	∅	Right	ORDNUM

information contained on this file is obtained from the data base except field four (4), the time that the order was placed. The data base order file contains the month during which the order was received and the simulation requires a daily ordering frequency. Conversion of the time of receipt from a monthly to a daily basis was made by determining the working days in each month of the study period and uniformly distributing the orders received in the month over the working days in the month. The calculated time of order receipt was determined in terms of cumulative working days for the study period and then placed in field four of the file. The file is sorted in ascending order on field four so that the file is processed in chronological order as it is processed sequentially.

The inventory file contains the inventory status of all the finished goods and components. The file specifications are shown in Table 2. Fields four, five, nine, and eleven are the fields used to maintain control of the inventory. Field four contained the amount of the item currently in stock; field five is the amount of the item currently available for use in filling orders; this amount is the total amount of product in-stock and in process less any adjustments for stock already committed. For finished goods, field nine will show the amount of the in-process inventory of the item

Field	Information Contained	Size of Field	Data Type	Number of Decimal Places	Justification	Variable Name for Field
1	Part number code for item	5	Numeric	∅	Right	PNCOD2
2	Product code of item	2	Numeric	∅	Right	PRDCD2
3	Usage class code	1	Alpha-numeric	--	Right	--
4	Amount of item in stock	7	Numeric	∅	Right	INSTK2
5	Amount of item available	7	Numeric	∅	Right	AVAIL2
6	Reorder point	7	Numeric	∅	Right	MIN2
7	"Order up to" quantity	7	Numeric	∅	Right	MAX2
8	Volume of part (in^3)	7	Numeric	2	Right	PCUIN2
9	Amount required for order filling	7	Numeric	∅	Right	REQPT2
10	Amount recommended for production	7	Numeric	∅	Right	RECPD2
11	Reserve for future assembly	7	Numeric	∅	Right	RESSTK

Table 2. Field Specifications of Inventory File

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Field	Information Contained	Size of Field	Data Type	Number of Decimal Places	Justification	Variable Name for Field
12	Standard cost of part	9	Numeric	4	Right	STCST2
13	Recommended for production	1	Numeric	$\emptyset$	Right	RFPEL2
14	Pieces per piece	1	Numeric	$\emptyset$	Right	PCPER2

Table 2.   (Continued)

that has already been assigned to fill outstanding customer orders upon completion. For component parts, field nine will again reflect the amount of the in-process inventory of the item committed for use in filling outstanding orders; additionally, field eleven will show the amount of the in stock inventory which has been assigned to an outstanding order which cannot yet be assembled due to the unavailability of another component of the finished good that was ordered. The file is stored sequentially and is accessed randomly.

The bill of materials file contains the list of components and the quantity of each which is required in the manufacture of each finished good. A maximum of six (6) components per finished good was adequate for all parts in this sequentially ordered (by part number code) direct access file. The file specifications are shown in Table 3.

The inverted bill of materials file or the where used file, is a listing by component of all the finished goods that use the component and the quantities that the manufacture of each finished good requires. This file is used to determine additional requirement of components for other finished goods when the component must be manufactured for one of the finished goods using it. The where used file specifications are shown in Table 4.

Field	Information Contained	Size of Field	Data Type	Number of Decimal Places	Justification	Variable Name for Field
1	Part number code of finished good	5	Numeric	0	Right	PNCDFG
2	Product code	2	Numeric	0	Right	PRDCD
3	Part number code of component one	5	Numeric	0	Right	COMP(1)
4	Quantity of component one used in finished good	7	Numeric	0	Right	COMPQ(1)
5	Part number code component two	5	Numeric	0	Right	COMP(2)
6	Quantity of component two used in finished good	7	Numeric	4	Right	COMPQ(2)
7	Part number code component three	5	Numeric	0	Right	COMP(3)
8	Quantity of component three used in finished good	7	Numeric	4	Right	COMPQ(3)
9	Part number code component four	5	Numeric	0	Right	COMP(4)

Table 3. Field Specifications - Bill of Materials File

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Field	Information Contained	Size of Field	Data Type	Number of Decimal Places	Justification	Variable Name for Field
10	Quantity of component four used in finished good	7	Numeric	4	Right	COMPQ(4)
11	Part number code component five	5	Numeric	Ø	Right	COMP(5)
12	Quantity of component five used in finished good	7	Numeric	4	Right	COMPQ(5)
13	Part number code of component six	5	Numeric	Ø	Right	COMP(6)
14	Quantity of component six used in finished good	7	Numeric	4	Right	COMPQ(6)

Table 3 (Continued)

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Field	Information Contained	Size of Field	Data Type	Number of Decimal Places	Justification	Variable Name for Field
1	Part number code of component	5	Numeric	Ø	Right	COMP(I)
2	Record sequence number	3	Numeric	Ø	Right	SEQ
3	Product code	2	Numeric	Ø	Right	PRDCD
4	Part number code of finished good one using this component	5	Numeric	Ø	Right	FGPNUC(1)
5	Quantity of component finished good one	7	Numeric	4	Right	CUFG(1)
6	Part number code of finished good two using this component	5	Numeric	Ø	Right	FGPNUC(2)
7	Quantity of component finished good two	7	Numeric	4	Right	CUFG(2)
8	Part number code of finished good three using this component	5	Numeric	Ø	Right	FGPNUC(3)
9	Quantity of component finished good three	7	Numeric	4	Right	CUFG(3)

Table 4. Field Specifications - Where Used File

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Field	Information Contained	Size of Field	Data Type	Number of Decimal Places	Justification	Variable Name for Field
10	Part number code of finished good four using this component	5	Numeric	Ø	Right	FGPNUC(4)
11	Quantity of component finished good four	7	Numeric	4	Right	CUFG(4)
12	Part number code of finished good five using this component	5	Numeric	Ø	Right	FGPNUC(5)
13	Quantity of component finished good five	7	Numeric	4	Right	CUFG(5)
14	Part number code of finished good six using this component	5	Numeric	0	Right	FGPNUC(6)
15	Quantity of component finished good six	7	Numeric	4	Right	CUFG(6)

Table 4 (Continued)

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Field two is used to identify additional records if more than six finished goods use a particular component; if so, additional records are included in the file until all finished goods using the component are included in the file.

GASP File Specifications

The simulation model uses five GASP files during execution. These files were the event file, the orders held for completion of component manufacture file, the orders held for finished goods assembly file, and the recommended for production list, which is kept in two different sequences which we will call two files.

The event file is used to store all of the events that occur during the simulation. There are four types of events allowed: a beginning of day event, an end of scheduling event, a receipt of component event, and a receipt of finished goods event. The information contained in each of the ten (10) fields of the record are shown in Table 5; each field is contained in one word of computer storage. The file is arranged in ascending sequence of event time (field one) and is accessed sequentially.

The fields used in the orders held files and the recommended for production file are shown in Table 6. The orders held for components file contains one record

Event / Field	Beginning of Day Event	End of Scheduling Period Event	Receipt of Component Event	Receipt of Finished Good Event
1	Time of event occurrence	Time of event occurrence	Time of event occurrence	Time of event occurrence
2	Event code (=2)	Event code (=4)	Event code (=3)	Event code (=5)
3	Not used	Not used	Product code of component to be received	Product code of finished good to be received
4	Not used	Not used	Part number code of component to be received	Part number code of finished good to be received
5	Not used	Not used	Quantity of component to be received	Quantity of finished good to be received
6	Not used	Not used	Day that order for which this component will be used was received	Day that order for which this receipt is for was received

Table 5. Field Specifications of Event File

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Event Field	Beginning of Day Event	End of Scheduling Period Event	Receipt of Component Event	Receipt of Finished Good Event
7	Not used	Not used	Order no. that component is for	Order no. that this receipt is for
8	Not used	Not used	Finished goods part no. that component is for	Not used
9	Pointer to successor entry in filing array	Pointer to succeeding entry in filing array	Pointer to succeeding entry in filing array	Pointer to succeeding entry in filing array
10	Pointer to preceding entry in filing array	Pointer to preceding entry in filing array	Pointer to preceding entry in filing array	Pointer to preceding entry in filing array

Table 5 (Continued)

File Field	Orders Held for Completion Components Manufacturing File	Orders Held for Finished Goods Assembly File	Recommended for Production List
1	Product code of component holding order	Product code of finished good held for assembly	Product code of component recommended
2	Part number code of component holding order	Part number code of finished good to be assembled	Part number code of component for which production is required
3	Order number held by this component	Order number held for assembly	Part number code of finished good which required the component to fill order
4	Part number code of finished good that will be made from this component	Number of sets to be assembled before order is complete	Day order received
5	Number of components needed before assembly can begin	Day order was received	Order number
6	Total number of sets of finished goods to be assembled for this order	Not used	Number of pieces to be manufactured

Table 6. Field Specifications for the Orders Held Files and Recommended for Production List

File Field	Orders Held for Completion Components Manufacturing File	Orders Held for Finished Goods Assembly File	Recommended for Production List
7	Day order was Received	Not used	Number of sets to be made to fill order
8	Not used	Not used	Not used
9	Pointer to succeeding entry in filing array	Pointer to succeeding entry in filing array	Pointer to succeeding entry in filing array
10	Pointer to pre- ceding entry in filing array	Pointer to pre- ceding entry in filing array	Pointer to preceding entry in filing array

Table 6 (Continued)

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for each component that is holding up the assembly of an order; the file is sorted in ascending order of time at which the order was received (field seven). The held for assembly file contains one record for each outstanding order and is sorted in ascending sequence of time of order receipt. The recommended for production list contains one record for each component that must be manufactured to meet each outstanding order. This file is sorted on order number and resorted by component number during processing.

Data Deck Specifications

The data read in by the simulation program during execution and contains twenty-four different types of data cards. The first fifteen data card types are used for specification of initial values of the non-GASP variables and the remaining data card types are used in initialization of the GASP variables. The card formats are shown in Table 7.

The first data card contains information pertaining to the type of output desired. The first three fields are used to determine if initial, intermediate, and/or final summary reports are desired. The remaining fields are used for specification of debugging and trouble shooting options, allowing for tracing and output of files at intermediate points in the program.

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The second data card contains the minimum release size to be tested during the simulation experiment, the assembly time, or the time period required to assemble or complete finished goods from available, completed components, the time period required to manufacture components from raw materials, and the time period between generation of successive production schedules.

Information concerning the starting inventory values is input via the next four cards. Data cards three and four list the dollar value, number of sets, and volume of the finished good and component inventories respectively. Data cards five and six contain the above data for the manufacturing-in-process and assembly-in-process files; in addition, the percentage of the standard cost that the average item in these inventories should be evaluated. This percentage of standard cost reflects the cost of materials for the component or finished good being manufactured or assembled and the amount of labor that has, on the average been expended upon the item. These figures were obtained from summations made during file initialization and use of data from cost accounting.

Data for the histograms to be printed is provided via data cards seven, eight, and nine. The first two of these histogram cards contain information about the cells in the individual histograms; the first card contains the lower bound of cell two in each (up to ten

total) histogram and the second contains the widths of the cells in each histogram. The third card contains the symbols to be used in the actual plotting of the histogram; the first symbol will represent (on the graph) the proportion of times a value within a particular cell was observed and the second symbol will be used to fill the rest of the line on the graph and represent the proportion of time cells other than the particular cell were observed.

Descriptive information about the product line under study and the purposes of the particular simulation experiment is contained on cards ten through fifteen. Card eleven contains up to sixteen (16) alphanumeric characters which describe the product line under study. The purpose or a description of simulation experiment is placed on the next five (5) data cards, up to eighty (80) characters on each card.

The rest of the data deck consists of data required by the GASP-II simulation program. There are up to eight different types of data cards required. The first of the GASP cards, card sixteen of the data deck contains clerical data for the GASP output. This data includes programmer name, project number, date of the run and the number of simulation experiments to be run during this program execution run. Data card seventeen also contains information concerning the GASP files and tables (arrays) stored in core. The fields of this card define:

the number of parameter (for statistical distributions sampled during execution) cards to be input, the number of histograms that will be generated, the number of variables for which statistics about their occurrence will be collected, the number of variables for which time integrated statistics will be kept, the maximum number of "file" entries that can be accommodated in the filing array, the maximum number of fields in any record in the filing array, the number of files that will be contained in the filing array, the maximum number of cells in any histogram, and a scale factor to avoid fixed point truncation errors in values stored in the filing array NSET.

The third data card type required by GASP contains the number of cells in each histogram, exclusive of the two end cells; the lower bound of the second cell and the cell width for the histograms being defined on cards seven and eight.

Data cards nineteen and twenty (GASP data cards four and five) contain data describing how the GASP files are to be stored in the filing array NSET. Card nineteen contains the number of the field upon which the particular GASP file will be sorted and stored. Card twenty is used to specify ascending or descending order for the sort.

GASP data cards of type six are optional; they
contain the parameter(s) of statistical distribution(s)
used during the simulation. The number of type six
cards that must be included is equal to the number of
parameter cards specified in field one of GASP data card
two (data card seventeen).

The GASP type seven data card contains information
relating to starting parameters, stopping rules, and
reinitialization procedures between successive experi-
ments in the same run. The values placed on the card
specify stopping rule, whether or not to clear (rezero)
the statistical storage areas between experiments, whether
or not to print a summary report between runs, the GASP
data card type at which reading of data for the next
experiment is to begin, the time to which the simulation
clock should be set at the beginning of the experiment,
if the value of the random number seed is zero; the
time that the simulation should end, given that this
type of stopping rule was specified, and a seed for the
random number generator.

The GASP type eight data cards are used to set
initial values in the GASP files. Each file entry con-
sists of a two card set, the first card of the set con-
tains the number of the file into which the record is to
be placed and the first seven (7) attributes; the second
card contains the remaining eight (8) attributes. There

are two required data sets. The first required set must
be the first set in the data deck and contain a minus
one (-1) for its file number; this will trip the initial-
ization of the filing array. The second required set
must be the last set supplied and it consists of a
zero (∅) for its file number and acts as the sentenal
for the end of type 8 data cards for the experiment.

Card 1

Field	Information Contained	Size of Field	Data Type	Number of Decimal Places	Justification	Variable Name for Field
1	Initial summary report Print flag Ø=no print ≠Ø=print	3	Numeric	Ø	Right	PRNT1
2	Intermediate report Print flag Ø=no print ≠Ø=print	3	Numeric	Ø	Right	PRNT2
3	Final report Print flag Ø=no print ≠Ø=print	3	Numeric	Ø	Right	PRNT3
4	Order information Print flag Ø=no print ≠Ø=print	3	Numeric	Ø	Right	PRNT4
5	Trace order path Print flag Ø=no print ≠Ø=print	3	Numeric	Ø	Right	PRNT5
6	Receipt of component information Print flag Ø=no print ≠Ø=print	3	Numeric	Ø	Right	PRNT6

Table 7. Data Card Specifications

Card 1 (Cont.)

Field	Information Contained	Size of Field	Data Type	Number of Decimal Places	Justification	Variable Name for Field
7	Trace receipt of component Print flag Ø=no print ≠Ø=print	3	Numeric	Ø	Right	PRNT7
8	Receipt of finished good information Print flag Ø=no print ≠Ø=print	3	Numeric	Ø	Right	PRNT8
9	Trace receipt of finished good Print flag Ø=no print ≠Ø=print	3	Numeric	Ø	Right	PRNT9
10	Print core files at end of scheduling period Print flag Ø=no print ≠Ø=print	3	Numeric	Ø	Right	PRNT1Ø
11	Not used	3	Numeric	Ø	Right	PRNT11
12	Print recommended for production file at end of scheduling period Print flag Ø=no print ≠Ø=print	3	Numeric	Ø	Right	PRNT12

Table 7 (Continued)

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Card 1 (Cont.)

Field	Information Contained	Size of Field	Data Type	Number of Decimal Places	Justification	Variable Name for Field
13	Not used	3	Numeric	Ø	Right	PRNT13
14	Not used	3	Numeric	Ø	Right	PRNT14
15	Not used	3	Numeric	Ø	Right	PRNT15

Card 2

Field	Information Contained	Size of Field	Data Type	Number of Decimal Places	Justification	Variable Name for Field
1	Minimum release size	1Ø	Numeric	Ø	Right	RELSIZ
2	Assembly time (completed components to completed finished goods)(working days)	1Ø	Numeric	Ø	Right	ASSTIM
3	Manufacturing time (from raw material to completed components) (days)	1Ø	Numeric	Ø	Right	MEGTDY
4	Number of working days	1Ø	Numeric	Ø	Right	SCHFRQ

Table 7 (Continued)

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Field	Information Contained	Size of Field	Data Type	Number of Decimal Places	Justification	Variable Name for Field
Card 3						
1	Starting value of finished goods inventory (dollars)	10	Numeric	2	Right	INVAL
2	Starting value of finished goods inventory (number of sets)	10	Numeric	2	Right	INQTY
3	Starting value of finished goods inventory (number of cubic inches)	10	Numeric	2	Right	INCUB
Card 4						
1	Starting value of component inventory (dollars)	10	Numeric	2	Right	CINVAL
2	Starting value of component inventory (number of sets)	10	Numeric	2	Right	CINQTY
3	Starting value of component inventory (number of cubic inches)	10	Numeric	2	Right	CINCUB

Table 7 (Continued)

106

Field	Information Contained	Size of Field	Data Type	Number of Decimal Places	Justification	Variable Name for Field
Card 5						
1	Starting value of work in process inventory (dollars)	1∅	Numeric	2	Right	WIPNAL
2	Starting value of work in process inventory (number of sets)	1∅	Numeric	2	Right	WIPQTY
3	Starting value of work in process inventory (number of cubic inches)	1∅	Numeric	2	Right	WIPCUB
4	Percentage of standard cost at which to evaluate work in process inventory	1∅	Numeric	2	Right	PRCNT1

Table 7 (Continued)

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Field	Information Contained	Size of Field	Data Type	Number of Decimal Places	Justification	Variable Name for Field
Card 6						
1	Starting value of as-sembly in process inventory (dollars)	10	Numeric	2	Right	AIPVAL
2	Starting value of assembly in process inventory (number of sets)	10	Numeric	2	Right	AIPQTY
3	Starting value of assembly in process inventory (number of cubic inches)	10	Numeric	2	Right	AIPCUB
4	Percentage of standard cost at which to eval-uate assembly in process inventory	10	Numeric	2	Right	PRCNT2
Card 7						
1-10	Lower bound of cell two of histogram one through ten	8	Numeric	4	Right	CELBND(I), I=1, 10

Table 7 (Continued)

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Field	Information Contained	Size of Field	Data Type	Number of Decimal Places	Justification	Variable Name for Field
Card 8						
1-10	Width of each cell in histogram one through ten	8	Numeric	4	Right	WIDTH(I), I=1, 1Ø
Card 9						
1	Symbol to be used on histograms	1	Alpha-numeric	-	Right	ASTRIK
2	Blank - used as symbol on histograms	1	Alpha-numeric	-	Right	BLANK
Card 10						
1-4	Four characters of the name of product line under study	4	Alpha-numeric	-	Left	A(I) I=1, 4
Cards 11-15						
1-20	A line of additional information about the simulation	4	Alpha-numeric	-	Left	A(I)

Table 7 (Continued)

Field	Information Contained	Size of Field	Data Type	Number of Decimal Places	Justification	Variable Name for Field
Card 16						
1	Name of simulator	12	Alpha-numeric	-	Left	NAME(I) I=1,6
2	Project number	4	Numeric	$\emptyset$	Right	NPROJ
3	Month of run	2	Numeric	$\emptyset$	Right	MON
4	Day of run	2	Numeric	$\emptyset$	Right	NDAY
5	Year of run	4	Numeric	$\emptyset$	Right	NYEAR
6	Number of simulation experiments for this run	4	Numeric	$\emptyset$	Right	NRUNS
Card 17						
1	Number of parameters (must be $\leq 1\emptyset$)	5	Numeric	$\emptyset$	Right	NPRMS
2	Number of histograms (must be $\leq 1\emptyset$)	5	Numeric	$\emptyset$	Right	NHIST

Table 7 (Continued)

Field	Information Contained	Size of Field	Data Type	Number of Decimal Places	Justification	Variable Name for Field
Card 17 (Cont.)						
3	Number of observed variables for which statistics are to be collected (must be ≤ 3∅)	5	Numeric	∅	Right	NCLCT
4	Number of variables for which time integrated statistics are to be taken (must be ≤ 3∅)	5	Numeric	∅	Right	NSTAT
5	Number of columns in filing array NSET	5	Numeric	∅	Right	ID
6	Maximum number of attributes of any entry in filing array (# rows in filing array)	5	Numeric	∅	Right	IM
7	Number of files in filing array (must be ≤ 1∅∅)	5	Numeric	∅	Right	NOQ

Table 7 (Continued)

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Field	Information Contained	Size of Field	Data Type	Number of Decimal Places	Justification	Variable Name for Field
Card 17 (Cont.)						
8	Maximum number of cells to be used in any histogram (must be ≤ 3∅)	5	Numeric	∅	Right	MXC
9	Scale to use to avoid truncation errors in fixed point array	1∅	Numeric	∅	Right	SCALE
Card 18						
1-1∅	Number of cells in histograms one thru ten (must be ≤ 3∅)	5	Numeric	∅	Right	NCELS(I), I=1, 1∅
Card 19						
1-1∅	Attribute or field of record upon which file is sorted	5	Numeric	∅	Right	KRANK(I) I=1, 10
Card 20						
1-1∅	Order of sorting for file: 1=ascending 2=descending	5	Numeric	∅	Right	INN(I)

Table 7 (Continued)

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Field	Information Contained	Size of Field	Data Type	Number of Decimal Places	Justification	Variable Name for Field
Card 21						
1-4	Parameters	10	Numeric	4	Right	PARAM(J, I) I=1, 4 J=1, NPARAM
Card 22						
1	Simulation stopping rule ∅ = programmer sup-plied + = end at TNOW ≥ TFIN − = programmer sup-plied	5	Numeric	∅	Right	MSTOD
2	SLFAR statistical storage areas between runs ∅ = not clear 1 = clear	5	Numeric	∅	Right	JCLR
3	Final GASP summary report to be printed ∅ = print 1 = not print	5	Numeric	∅	Right	NORPT

Table 7 (Continued)

113

Field	Information Contained	Size of Field	Data Type	Number of Decimal Places	Justification	Variable Name for Field
Card 22 (Cont.)						
4	Control variable for card type at which to begin read for second run	5	Numeric	Ø	Right	NEP
5	Value at which simu-lated time begins	1Ø	Numeric	3	Right	TBEG
6	Value at which simu-lation is to finish (if field 1 or card 21 is positive)	1Ø	Numeric	3	Right	TFIN
7	Seed for random no. generator, Ø = not changed between runs +,-= set equal to supplied value	4	Numeric	Ø	Right	JSEED

Table 7 (Continued)

Field	Information Contained	Size of Field	Data Type	Number of Decimal Places	Justification	Variable Name for Field
Card 23						
1	File number to which entry belongs -1 for start of data Ø for end of data	1Ø	Numeric	Ø	Right	JQ
2-7	Fields 1-6 of record	1Ø	Numeric	2	Right	ATRIB(I) I=1, 7
Card 24						
1-8	Fields 7-15 of record	1Ø	Numeric	2	Right	ATRIB(I) I=8, 15

Table 7 (Continued)

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3.4 Output Generated

The output of the simulation program is generated on an initial, intermediate, and final (cumulative) basis and is designed to provide information upon the number of setups, inventory, and customer service levels that would occur using the decision rule being tested in the simulation. The initial output provides an echo check on the parameters read into the simulation program.

The intermediate output provides a summary of the activity which occurred during the scheduling period. The number and time spent in set-up activities will be determined from the number of different components (job tickets) that are generated. The inventory levels at the end of each scheduling period is output so that any trend in these levels can be observed. These inventory level statistics are kept for four classes of inventory: finished goods inventory, component inventory, manufacturing (of components)-in-process and assembly (of finished goods from components)-in-process. The customer service level is determined by using the order disposition information: the total number of items ordered, the number of orders filled upon receipt, the number of orders partially filled, and the number of backorders.

The final summary report provides the cumulative values of the above statistics over the simulation. The

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mean, standard deviation, minimum, and maximum values
and number of observations are output for the job ticket,
inventory and customer service statistics. In addition
to these statistics, histograms showing the distribution
or order size, job ticket size and size of orders filled
upon receipt are provided.

3.5 Program Descriptions and Flowcharts

MAINPRG

The main program, MAINPRG, is used for initialization of the non-GASP variables, call subroutine OTPUT to generate an echo check of the values read in, and calls the GASP subroutine which controls the simulation. Upon return from GASP, the main program closes the files and terminates execution. The logic of the main program is flowcharted in Figure 26.

EVNTS

Subroutine EVNTS is used to pass program control to the set of subroutines which process the various events which occur in the simulation. This subroutine provides for any loading (overlaying) of the program phases that is necessary for proper program execution; this routine's logic is shown in Figure 27.

BEGNDY

This event subroutine is used to collect time integrated statistics on the four types of inventory, finished goods, component, manufacturin-in-process and assembly-in-process and to control the processing of orders for each day of the simulation via subroutine GETORD. The logic of subroutine BEGNDY is shown in Figure 28.

GETORD

This subroutine controls the processing of the
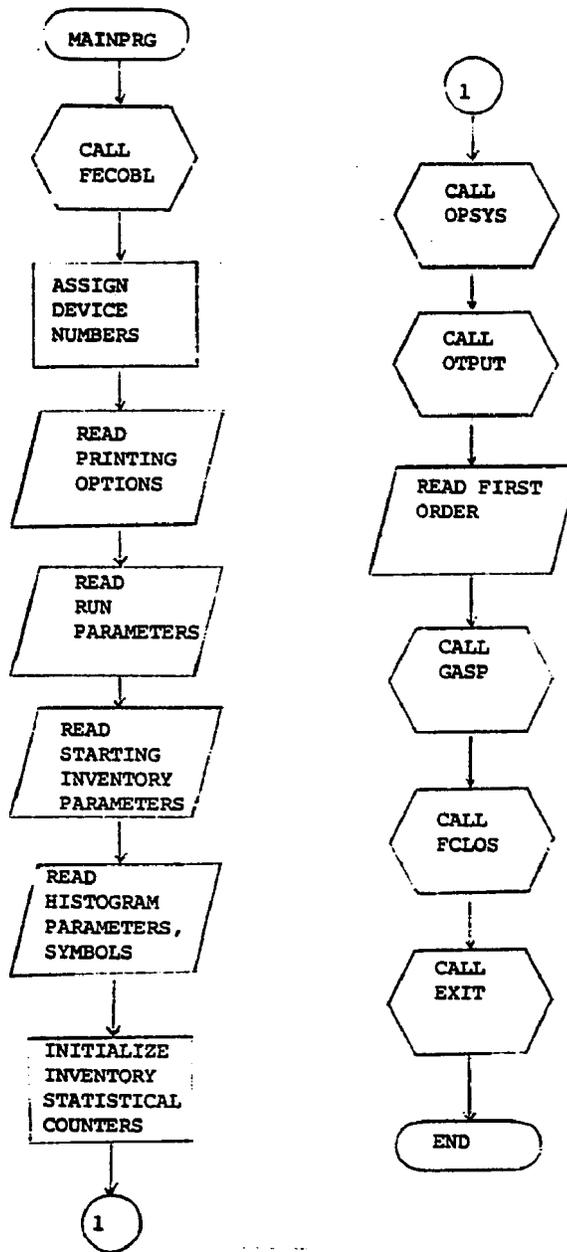
Figure 26. Logic of MAINPRG

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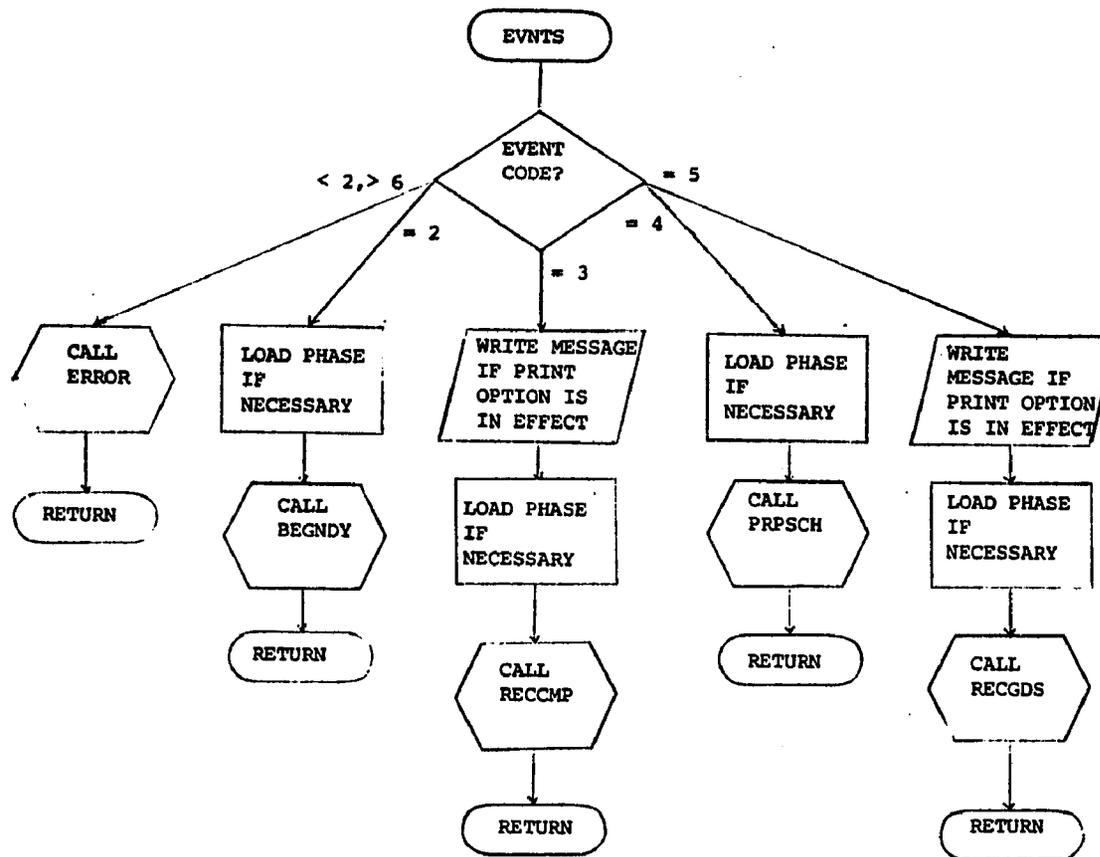
Figure 27. Logic of Subroutine EVNTS
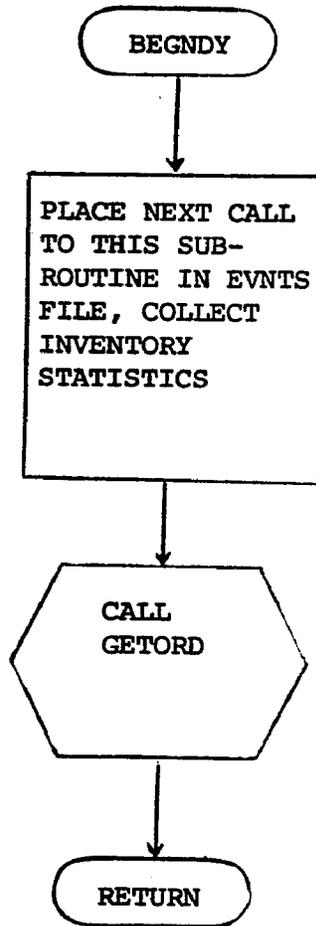
Figure 28. Logic of Subroutine BEGNDY

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PARFIL

The logic of the subroutine which processes orders which can be partially filled is shown in Figure 31. After calculation of the size of the filled and back-ordered portions of the order and the entry of the back-ordered portion on the orders held for assembly file, the subroutine determines if the finished good has been recommended for production during the current scheduling period. If it has been recommended, the amount of the goods needed to fill the backordered portion of the order and the amount of the goods needed for inventory, if any, are calculated and subroutine RFPLST called to determine if component inventory is sufficient to make the required goods and/or if the component(s) must be recommended for production. If the good has not been recommended and there is any of the good in process for inventory, part or all of the inventory will be allocated to fill the backordered portion and the need for additional inventory determined. If an additional quantity of the finished good is required or there is none of the desired item in process, subroutine RFPLST is called to allocate or recommend manufacture of suffi-cient component for the finished good. Statistics on the order are collected and the total inventory level counters are updated immediately before return to the calling subroutine.
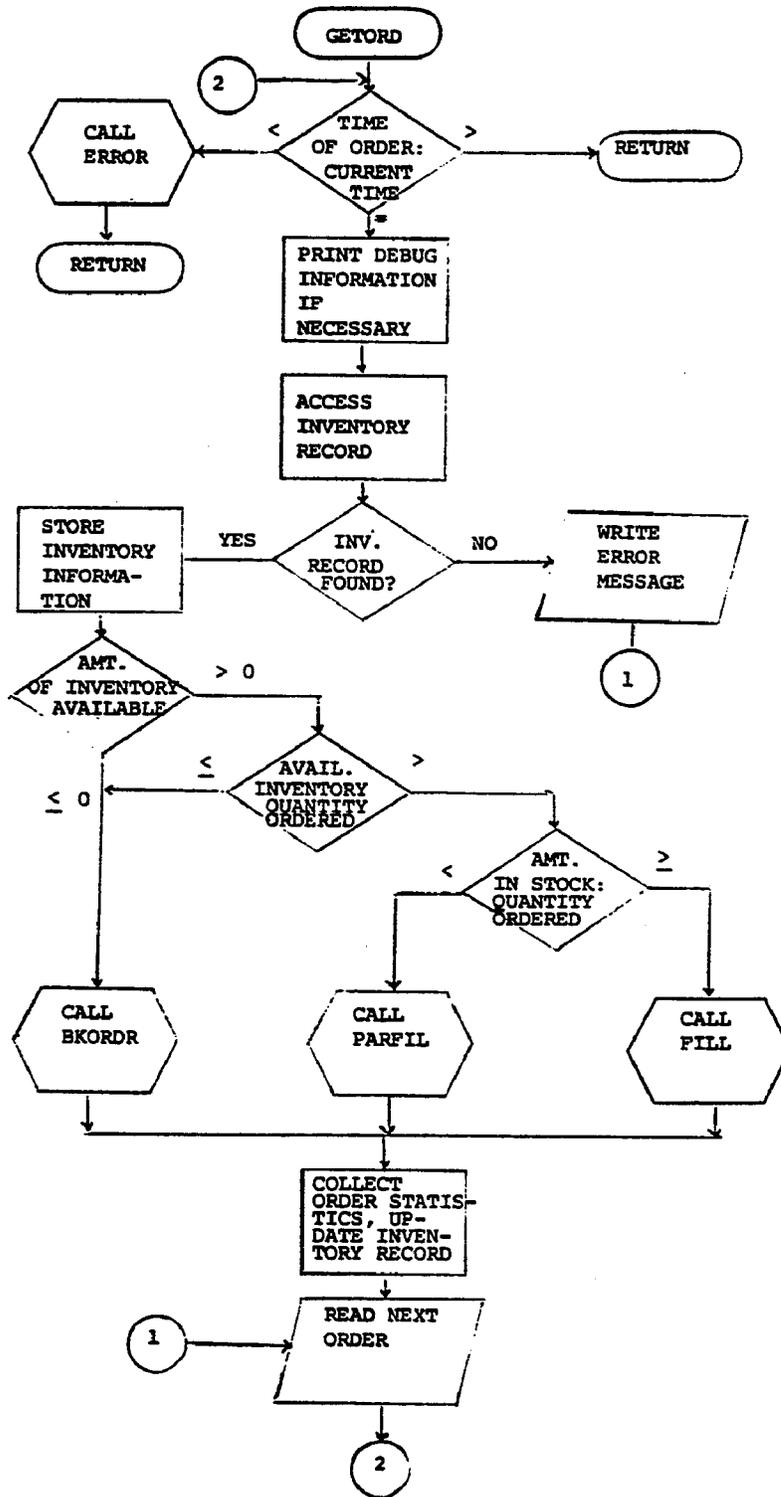
Figure 29. Logic of Subroutine GETORD

orders which occur during the simulation. The subroutine
is called once for each simulated day and process each
each order that is placed during the simulated day. The
routine accesses the inventory status of the finished
good ordered and on the basis of the in-stock and avail-
able quantities determines if the order can be filled,
partially filled, or backordered and calls the appro-
priate routines to process the order. This routine is
used to collect statistics on the sizes and disposition
of orders and updates the finished good's inventory
record to reflect the changes caused by the order.

FILL

Whenever an order can be filled from stock upon
receipt, subroutine FILL is called to reduce the in-
stock level and determine if the finished good that has
been ordered has been recommended for production during
the current scheduling period. If it has been recommended,
the amount of the order is added to the amount recom-
mended to be made. If it has not been recommended, the
reorder point is checked against the current inventory
level and if necessary the manufacture of the item is
ordered. In either case, the orders' statistics are
collected and the total inventory level is updated. The
logic for subroutine FILL is shown in Figure 30.

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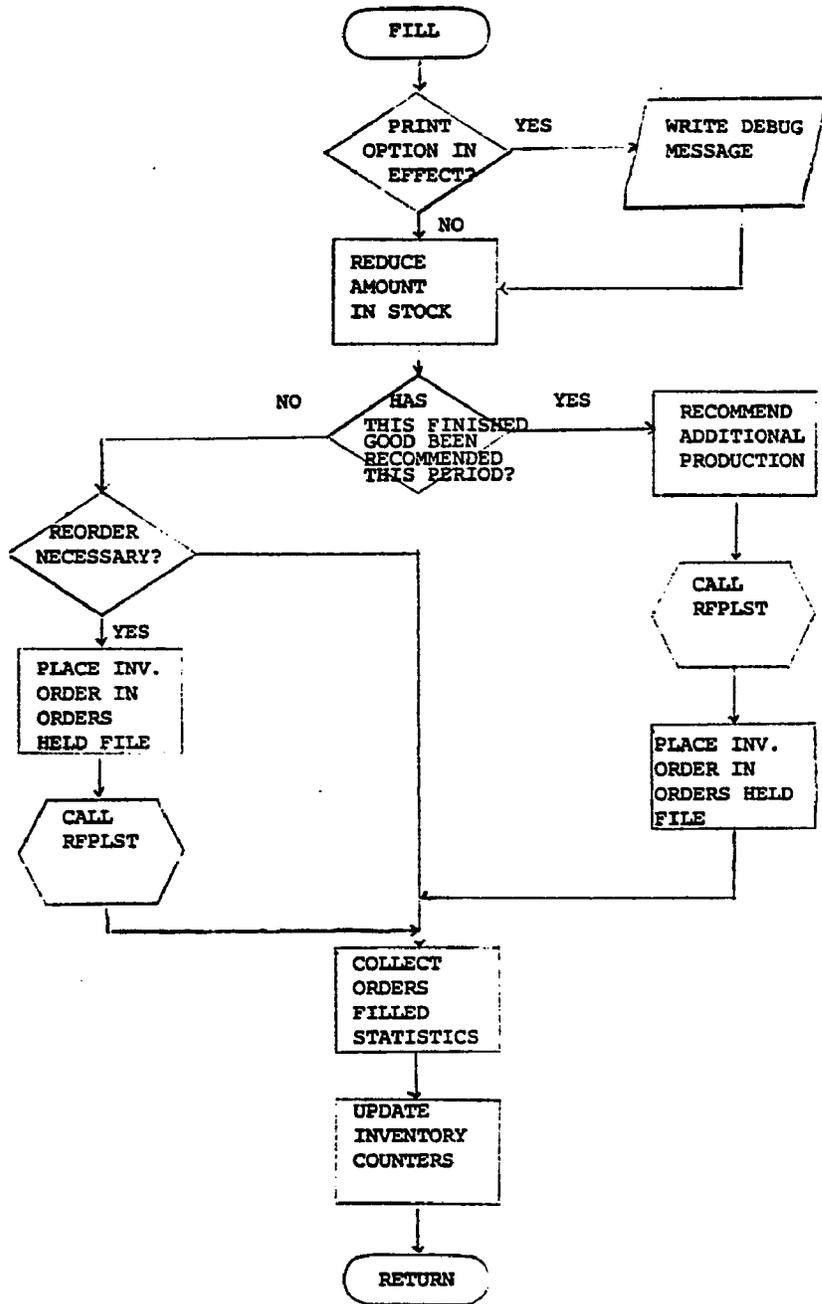
Figure 30. Logic of Subroutine FILL

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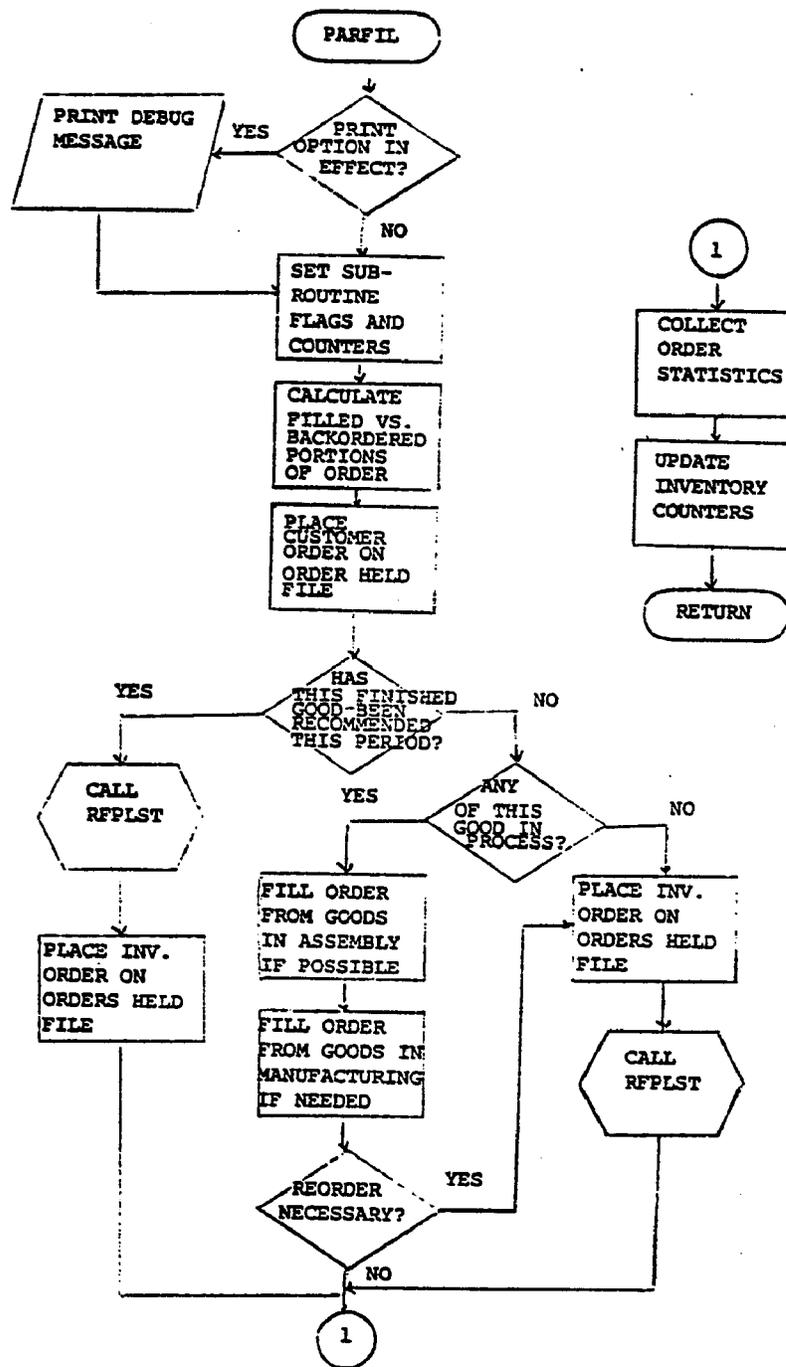
Figure 31. Logic of Subroutine PARFIL

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BKORDR

The logic of subroutine BKORDR processes the orders for which none of the item ordered is in stock at the time of order receipt. After the initialization of the subroutine counters, the subroutine determined if the item has already been placed upon the recommended for production list of this scheduling period. If not, the additional amount of component(s) needed to fill this order is calculated and allocated to the production of this item from component inventory or placed on the recommended for production list. If the item has not been recommended, the in-process inventories are checked and if a quantity of this good is available, part or all of this in process quantity is allocated to the order; if the item is not in process or if additional inventory is required due to the filling of the order, RFPLST is called to allocate components or recommend their production. In all cases statistics are collected on the order and the inventory statistics are collected. The logic is flowcharted in Figure 32.

RFPLST

Subroutine RFPLST is called whenever additional finished goods must be manufactured. This subroutine determines the amount of component(s) necessary for the completion of the desired finished good and allocates as much as feasible from the component inventory,
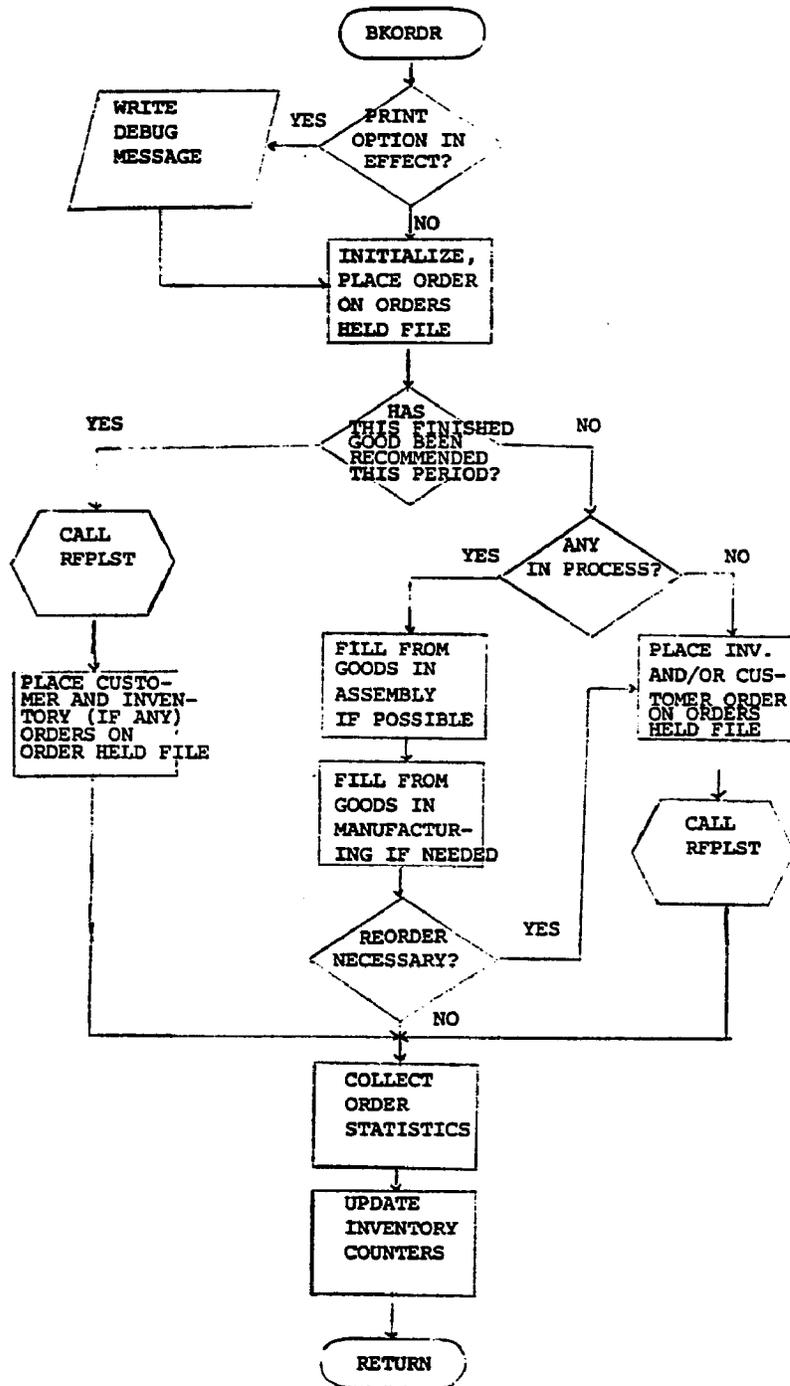
Figure 32. Logic of Subroutine BKORDR

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recommending for production for any additional amount of component either for the manufacture of product or for component inventory. The routine accesses the bill of materials file to obtain a list of all components and allocates and/or recommends production for the component as needed. For each component, the status of the component (not recommended, recommend with slack due to minimum release size, recommended with no slack) is determined. If the component has not been recommended for production during the current scheduling period, any in-stock or in-process inventory of the component necessary to fill the order are allocated and any additional amount of component needed for the order is recommended for production. If the component has already been recommended during the scheduling period, the slack is checked. Slack is the difference between current needs and the recommended production quantity, which may exist due to the minimum manufacturing lot size rule; e.g. if the minimum batch size being tested is one hundred (100) and the unrestricted recommended amount is fifty (50), a slack of fifty (50) exists for use in filling additional component requirements that may be necessitated by additional order receipt. If this slack exists, it is allocated and, if required, additional component is recommended. If no slack exists, the requirement of the current component is added to the quantity
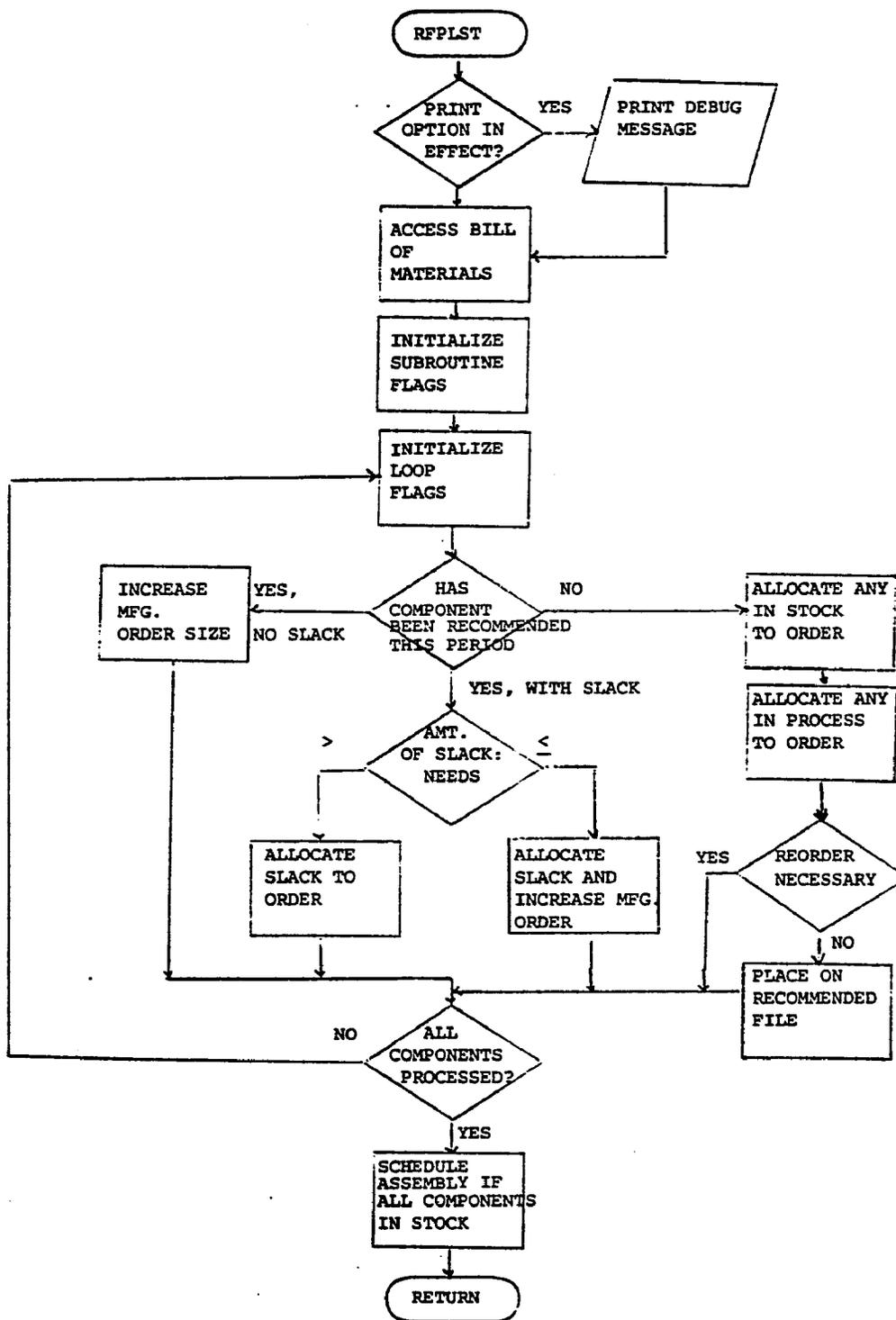
Figure 33. Logic of Subroutine RFPLST

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recommended for production.

After all components have been processed, a check
is made to determine if all of components needed were
in stock; if so, as much of the order is assembled as
possible. The flowchart of the logic for this subroutine
is shown in Figure 33.

SCHASS

Subroutine SCHASS (Figure 34) is called to schedule
the completion of assembly event for a finished good.
When this event is scheduled, the appropriate component
inventory records are updated to reflect the removal of
parts for the assembly. Total inventory counts for
component and manufacturing in process are also updated
by this routine.

RECCMP

This routine is used to process the receipt of
component into component inventory event. The routine
calculates the processing time and updates the work in
process and component inventory totals and the component
records. If the receipt of a component is for an out-
standing customer order, the amount of the component
holding up the assembly of the order is revised. If
this receipt supplies the remaining requirement of the
component for the order, a check is made to determine if
this component was the last one holding up assembly; if
so, the assembly of the order is scheduled. The logic
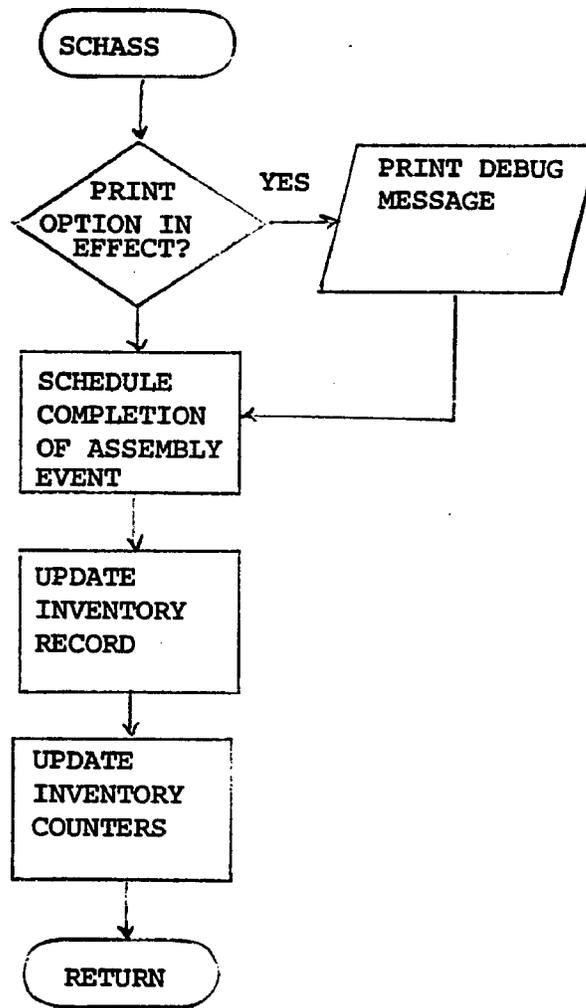
Figure 34. Logic of Subroutine SCHASS

of RECCMP is shown in Figure 35.

RECGDS

The processing of the receipt of finished goods into finished goods inventory from assembly event is performed by subroutine RECGDS. After calculation of the order wait time (Figure 36) and access of the inventory record, the receipt is determined to be either for inventory replenishment or to fill an outstanding customer order. If the receipt is for a customer order, it is shipped and the amount of the order outstanding is reduced. If the receipt is for inventory, it is placed in inventory. The amount of the inventory in process reduced. The individual product's finished goods inventory record is updated and the total finished goods inventory and assembly in process counters updated appropriately.

PRPSCH

This routine performs the scheduling activities that occur at the end of a scheduling period (Figure 37). The time of completion of the manufacturing operations for each component on the recommended for production list is determined and the receipt of component event scheduled. The component inventory records are updated to reflect the change from recommended to in-process status and the total work-in-process inventory counter updated. A summary of the scheduling period is printed via a call to subroutine OTPUT.
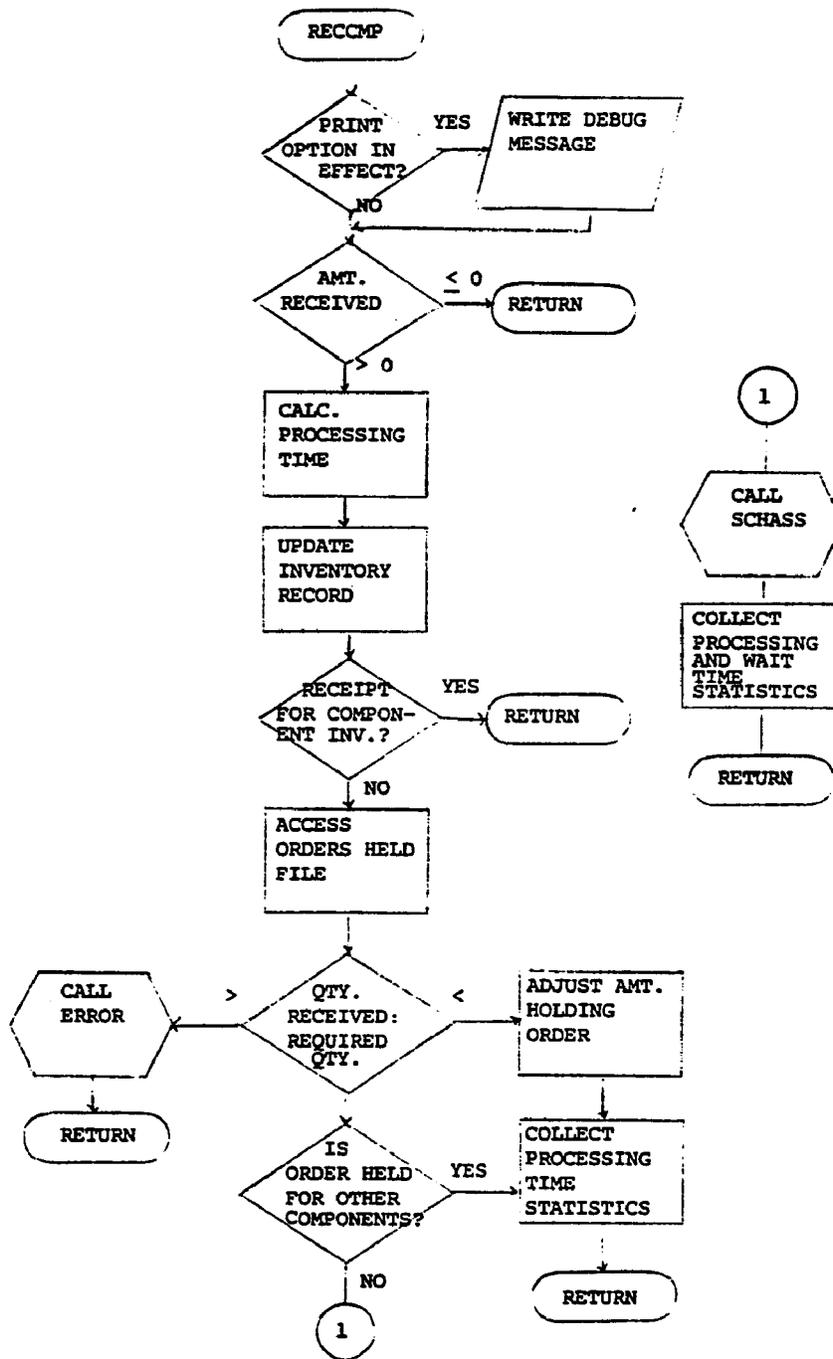
Figure 35 Logic of Subroutine RECCMP

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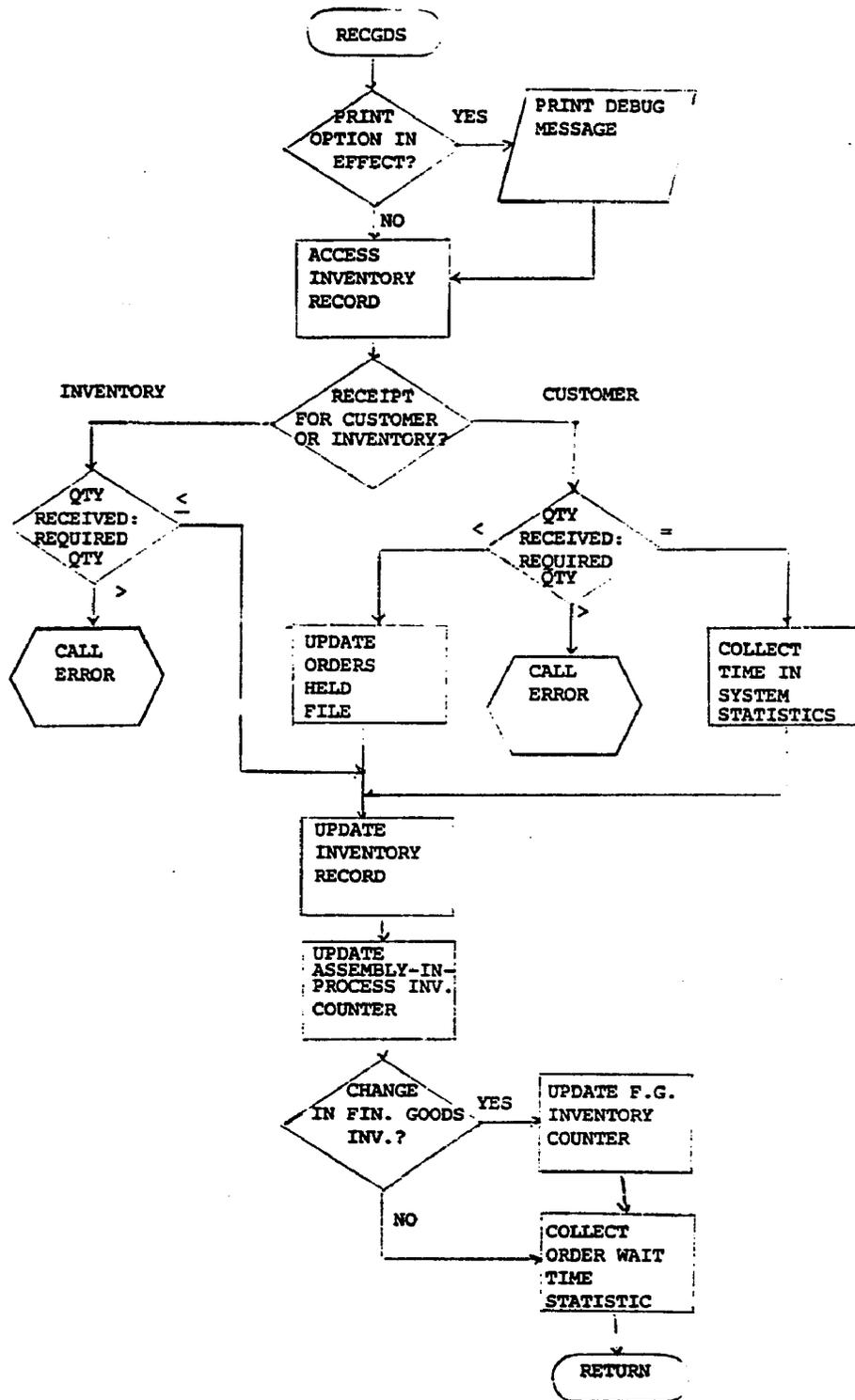
Figure 36 Logic of Subroutine RECGDS

135
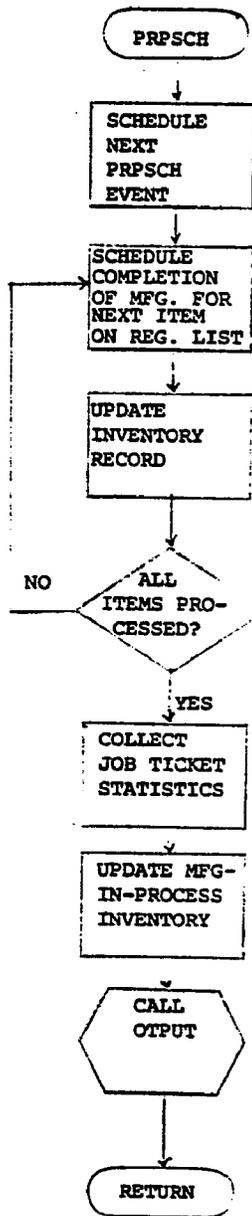
Figure 37. Logic of Subroutine PRPSCH

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OTPUT

This routine prints initial, intermediate and final summary reports when called for the observed variables (Figure 38).

SUMRY

This routine prints the time integrated statistics observed over the simulation and plots them in histogram form. As part of the final summary, (Figure 39).

DAINV

This subroutine provides a useful utility setting of values from the GASP arrays to be written onto or read from the direct access inventory file (Figure 40).

FILACC

This COBOL subroutine provides the linkage to the disk files. Desired records in the bill of materials, inverted bill of materials or inventory files may be accessed using this routine. The information exchange from the calling simulation subprogram to this routine is via a string of parameter fields. These fields may be used to transfer information read from the files by the routine or transfer information into the routine for storage in a record of the file. The logic of this routine is shown in Figure 41.

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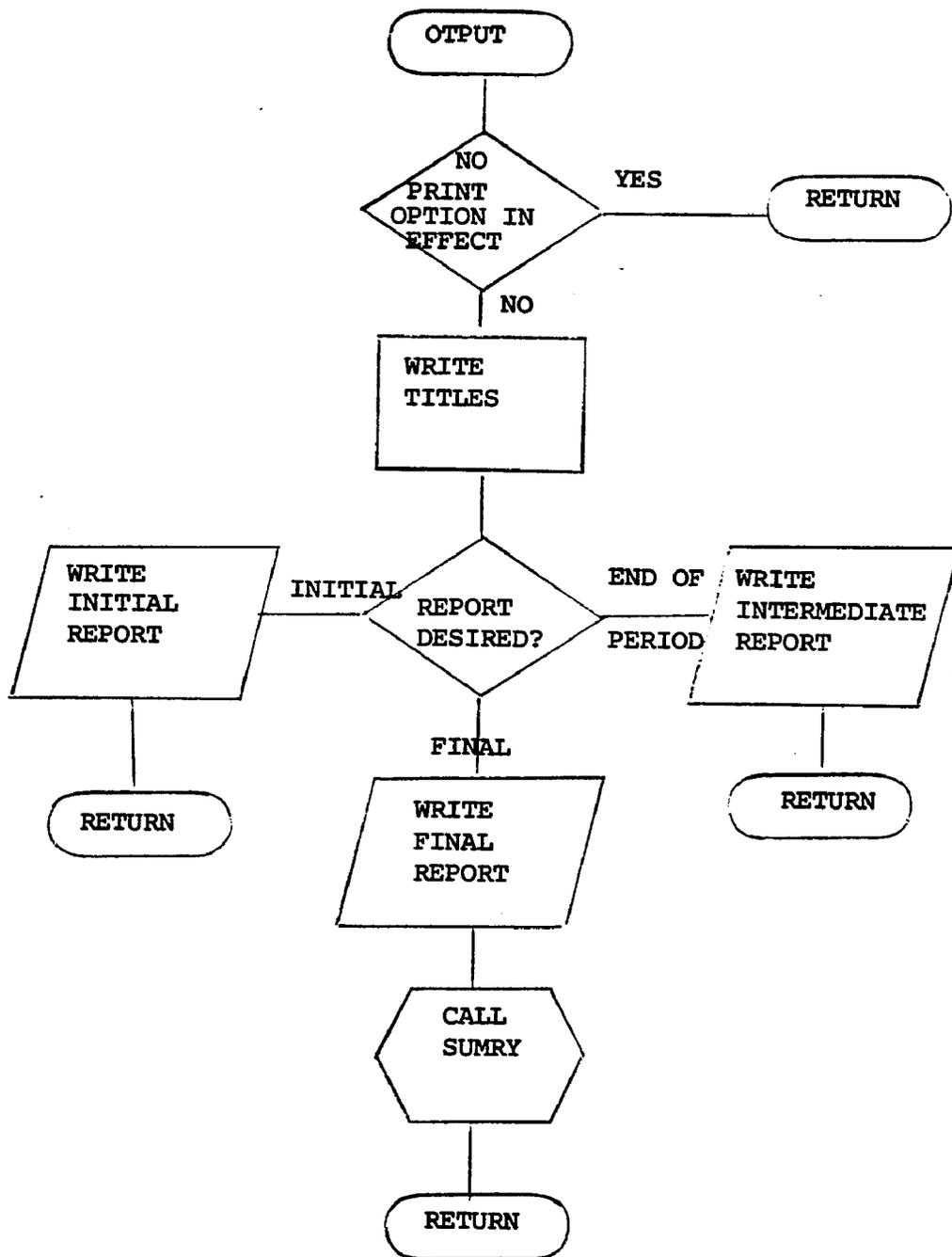
Figure 38. Logic of Subroutine OTPUT

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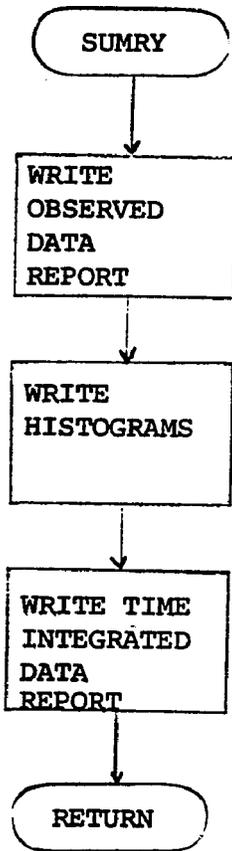
Figure 39. Logic of Subroutine SUMRY
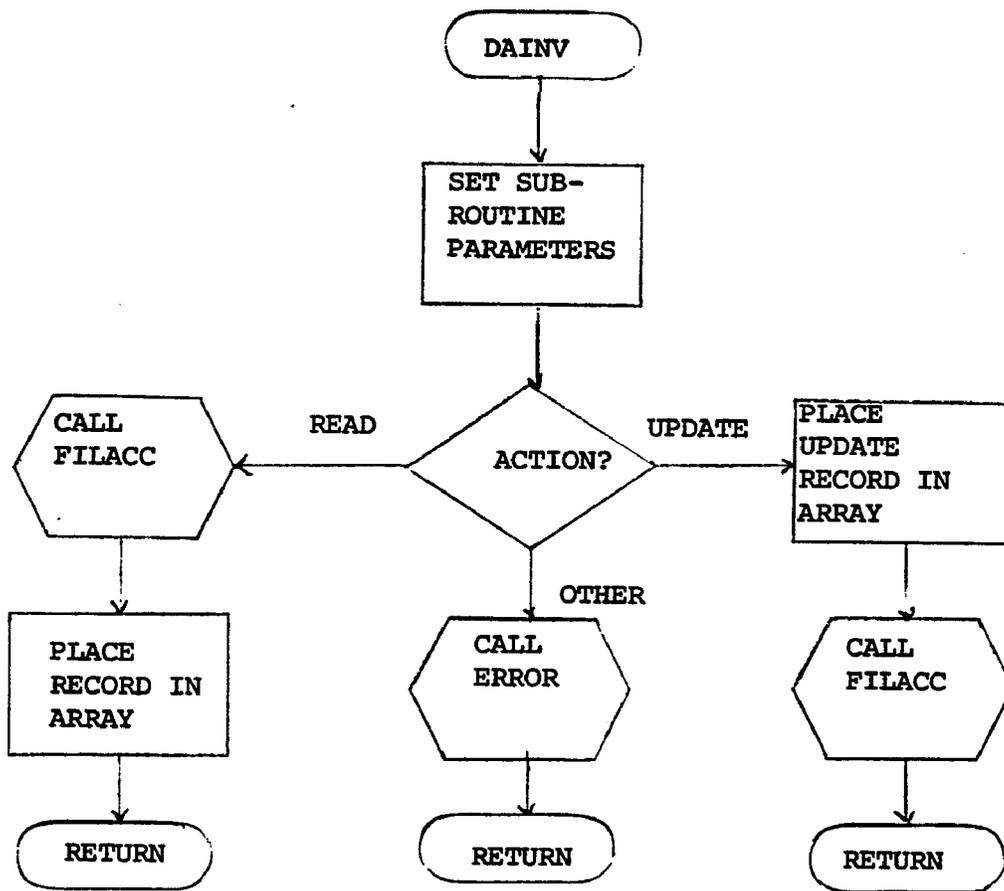
Figure 40.   Logic of Subroutine DAINV
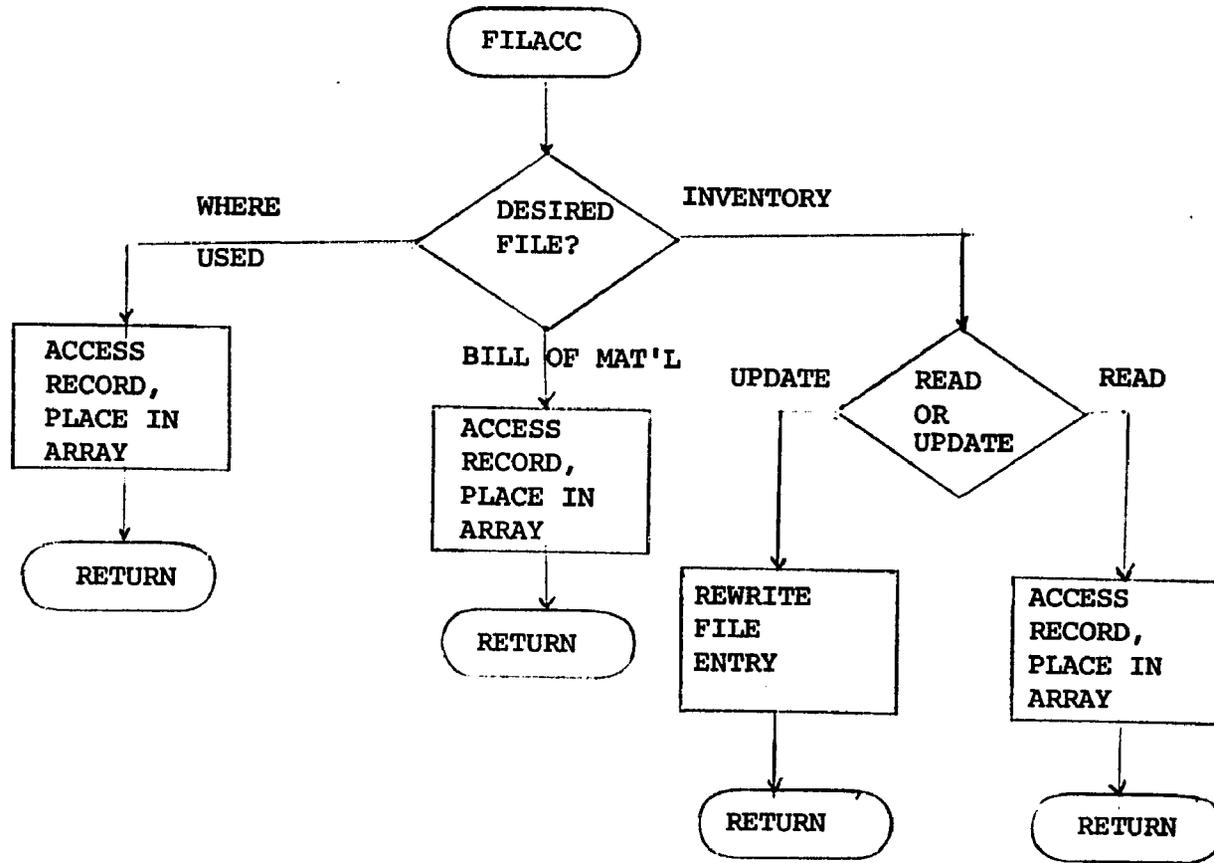
Figure 41. Logic of Subroutine FILACC

CHAPTER 4 DATA COLLECTED AND ITS ANALYSIS

4.1 Overview

The data analyzed in an effort to determine the effect of the introduction of a minimum manufacturing lot size decision rule was collected via simulation and sampling. Simulation provided time-series data on the number of job tickets issued, and the inventory levels that would occur under various levels of the decision rule. Sampling was used to gather information about the cost of setups for the products under study and the long term customer service levels.

A series of simulation experiments was used to test a range of values for the decision rule. The simulation was run using values of 0, 50, 100, 150, 200, 250, 300, 350, 400, and 500 pieces for the minimum batch size. Each simulation experiment was run using the same starting inventory conditions and order stream in order to isolate the effect of the decision rule on the inventory costs.

Sampling was used to estimate the set-up costs that would be eliminated by use of the minimum manufacturing lot size decision rules and to gauge the long term effects of the rules on customer service.

4.2 Job Ticket (Set-up) Data

Job tickets are the authorization for the manufacture of a particular component; each ticket issued authorizes one component's manufacture and therefore, the number of tickets issued can be used in estimating the set-up requirements under the various levels of the minimum manufacturing lot size decision rule tested.

The number of job tickets issued under the various levels of the decision rule is estimated via simulation of the manufacturing facility. The facility is scheduled on a weekly basis and the component requirements which result from order receipt during the week are aggregated into a production schedule at the end of the week. The number of job tickets issued at the end of each simulated scheduling period is shown in Table 8 and graphed in Figure 42.

The number of job tickets issued decreases as the minimum manufacturing lot size increases. This is evident from inspection of Table 9 which tabulated the difference in the number of job tickets issued for each scheduling period under the higher levels of the decision rule and the number of tickets issued under an unrestricted (zero) minimum lot size rule.

The analysis of the job ticket data will focus on the analysis of the differences in the number of job

WEEK	0.00	50.00	100.00	150.00	200.00	250.00	300.00	350.00	400.00	500.00
1	60.00	60.00	60.00	60.00	60.00	60.00	60.00	60.00	60.00	60.00
2	45.00	44.00	44.00	44.00	42.00	42.00	42.00	42.00	42.00	42.00
3	43.00	41.00	41.00	40.00	39.00	39.00	39.00	39.00	38.00	37.00
4	56.00	55.00	54.00	52.00	51.00	51.00	50.00	50.00	50.00	50.00
5	50.00	46.00	44.00	45.00	42.00	41.00	41.00	40.00	40.00	38.00
6	42.00	39.00	36.00	35.00	35.00	33.00	30.00	31.00	31.00	30.00
7	37.00	33.00	33.00	33.00	29.00	29.00	26.00	26.00	26.00	26.00
8	57.00	56.00	53.00	51.00	50.00	47.00	46.00	46.00	46.00	44.00
9	50.00	46.00	43.00	45.00	45.00	45.00	46.00	46.00	41.00	41.00
10	51.00	43.00	40.00	40.00	38.00	37.00	36.00	35.00	36.00	36.00
11	33.00	33.00	27.00	24.00	24.00	24.00	21.00	21.00	18.00	20.00
12	57.00	55.00	51.00	46.00	45.00	46.00	41.00	40.00	39.00	39.00
13	50.00	48.00	46.00	45.00	38.00	33.00	37.00	35.00	32.00	31.00
14	47.00	43.00	40.00	39.00	37.00	33.00	32.00	31.00	32.00	27.00
15	42.00	37.00	36.00	32.00	32.00	29.00	25.00	25.00	24.00	22.00
16	48.00	43.00	41.00	40.00	40.00	37.00	38.00	36.00	36.00	33.00
17	47.00	42.00	42.00	40.00	39.00	38.00	36.00	37.00	34.00	33.00
18	49.00	46.00	42.00	40.00	42.00	38.00	39.00	37.00	36.00	33.00
19	39.00	36.00	32.00	31.00	28.00	28.00	27.00	28.00	23.00	24.00
20	42.00	37.00	34.00	31.00	29.00	29.00	27.00	27.00	29.00	26.00
21	48.00	48.00	47.00	44.00	42.00	40.00	37.00	36.00	36.00	34.00
22	46.00	40.00	38.00	36.00	34.00	32.00	29.00	30.00	26.00	23.00
23	42.00	36.00	34.00	32.00	29.00	31.00	26.00	26.00	24.00	25.00
24	45.00	41.00	35.00	35.00	35.00	34.00	34.00	33.00	32.00	31.00
25	38.00	34.00	31.00	29.00	28.00	28.00	27.00	25.00	25.00	25.00
26	45.00	38.00	37.00	36.00	34.00	31.00	31.00	29.00	31.00	29.00
27	40.00	37.00	36.00	33.00	30.00	29.00	27.00	23.00	22.00	21.00
28	36.00	35.00	31.00	30.00	26.00	26.00	27.00	26.00	18.00	19.00
29	42.00	33.00	32.00	30.00	29.00	21.00	26.00	19.00	26.00	22.00
30	37.00	30.00	29.00	23.00	22.00	29.00	21.00	22.00	20.00	19.00
31	36.00	29.00	29.00	26.00	26.00	29.00	26.00	31.00	22.00	22.00
32	42.00	41.00	41.00	34.00	35.00	33.00	32.00	28.00	31.00	27.00
33	41.00	40.00	35.00	31.00	28.00	29.00	26.00	19.00	26.00	27.00
34	29.00	26.00	26.00	24.00	22.00	22.00	20.00	17.00	18.00	18.00
35	32.00	30.00	25.00	25.00	20.00	23.00	20.00			17.00

Table 8. Job Ticket Data

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*** RELEASE SIZES ***

* WEEK *	0.00	50.00	100.00	150.00	200.00	250.00	300.00	350.00	400.00	500.00
36	39.00	39.00	34.00	31.00	26.00	26.00	29.00	27.00	26.00	24.00
37	46.00	36.00	34.00	32.00	27.00	27.00	29.00	30.00	24.00	23.00
38	46.00	42.00	36.00	34.00	33.00	29.00	29.00	30.00	26.00	27.00
39	48.00	46.00	43.00	39.00	37.00	31.00	34.00	31.00	31.00	30.00
40	54.00	51.00	49.00	46.00	45.00	41.00	39.00	39.00	40.00	34.00
41	45.00	42.00	40.00	33.00	33.00	31.00	29.00	28.00	29.00	27.00
42	51.00	48.00	46.00	45.00	42.00	42.00	41.00	37.00	35.00	32.00
43	44.00	38.00	37.00	34.00	34.00	31.00	26.00	30.00	30.00	27.00
44	60.00	52.00	55.00	52.00	50.00	44.00	44.00	40.00	41.00	41.00
45	51.00	49.00	46.00	43.00	41.00	38.00	37.00	37.00	32.00	29.00

Table 8 (Continued)
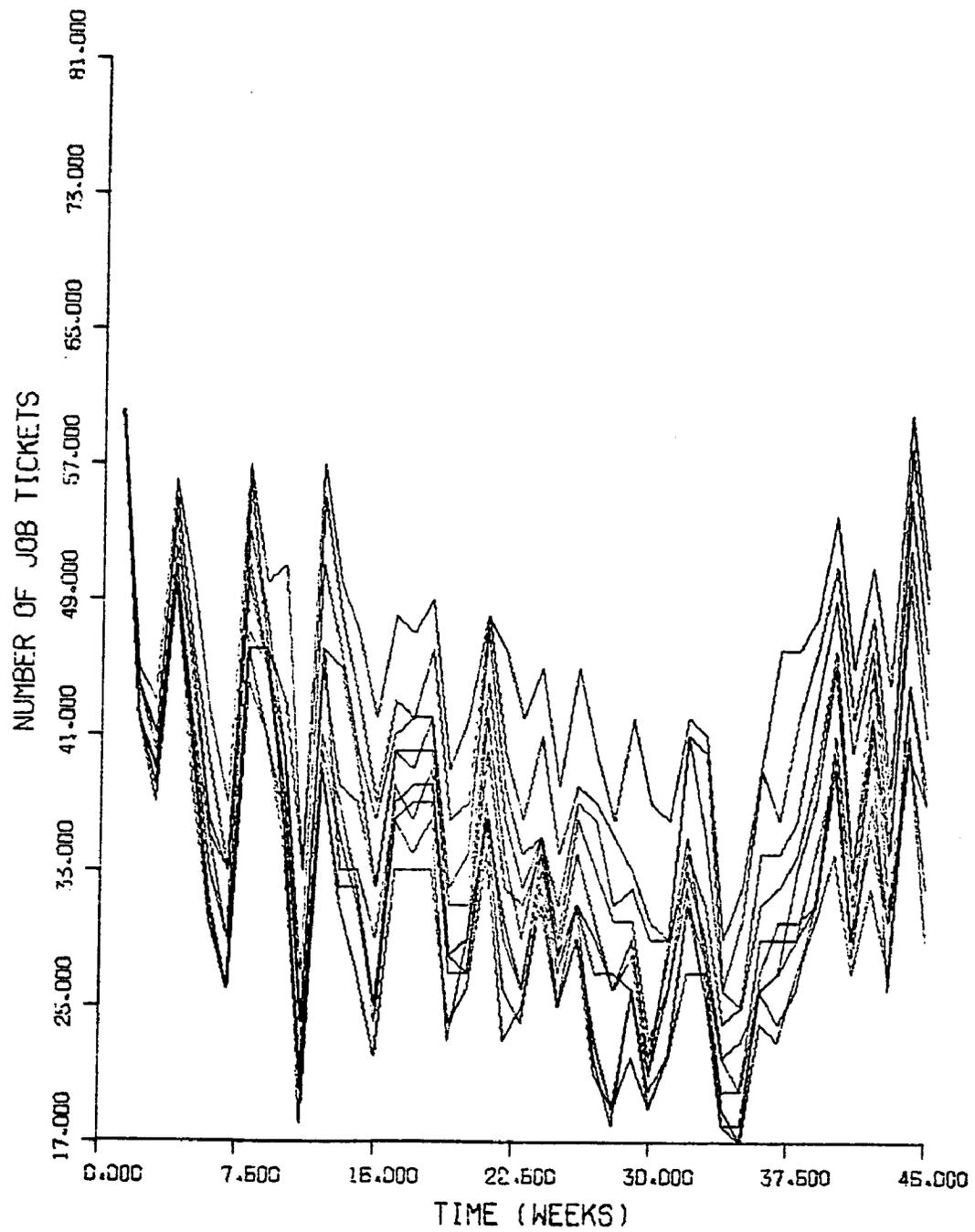
Figure 42. Plot of Number of Job Tickets

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WEEK	50.00	100.00	150.00	200.00	250.00	300.00	350.00	400.00	500.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	1.00	1.00	1.00	3.00	3.00	3.00	3.00	3.00	3.00
3	2.00	2.00	3.00	4.00	4.00	4.00	4.00	5.00	6.00
4	1.00	2.00	4.00	5.00	5.00	6.00	6.00	6.00	6.00
5	4.00	6.00	5.00	8.00	9.00	9.00	10.00	10.00	12.00
6	3.00	6.00	7.00	7.00	9.00	12.00	11.00	11.00	12.00
7	4.00	4.00	4.00	8.00	8.00	11.00	11.00	11.00	11.00
8	1.00	4.00	6.00	7.00	10.00	11.00	11.00	11.00	13.00
9	4.00	2.00	5.00	5.00	5.00	4.00	4.00	9.00	9.00
10	8.00	11.00	11.00	13.00	14.00	15.00	16.00	15.00	17.00
11	0.00	6.00	9.00	9.00	9.00	12.00	12.00	15.00	13.00
12	2.00	6.00	11.00	12.00	11.00	16.00	17.00	18.00	18.00
13	2.00	4.00	5.00	12.00	17.00	13.00	15.00	18.00	19.00
14	4.00	7.00	8.00	10.00	14.00	15.00	16.00	15.00	20.00
15	5.00	6.00	10.00	10.00	13.00	17.00	17.00	18.00	20.00
16	5.00	7.00	8.00	8.00	11.00	10.00	12.00	12.00	15.00
17	5.00	5.00	7.00	8.00	9.00	11.00	10.00	13.00	14.00
18	3.00	7.00	9.00	7.00	11.00	10.00	12.00	13.00	16.00
19	3.00	7.00	8.00	11.00	11.00	12.00	11.00	16.00	15.00
20	5.00	8.00	11.00	13.00	13.00	15.00	15.00	13.00	16.00
21	0.00	1.00	4.00	6.00	8.00	11.00	12.00	12.00	14.00
22	6.00	8.00	10.00	12.00	14.00	17.00	16.00	20.00	23.00
23	6.00	8.00	10.00	13.00	11.00	16.00	16.00	18.00	17.00
24	4.00	10.00	10.00	10.00	11.00	11.00	12.00	13.00	14.00
25	4.00	7.00	9.00	10.00	10.00	11.00	13.00	13.00	13.00
26	7.00	8.00	9.00	11.00	14.00	14.00	16.00	14.00	16.00
27	3.00	4.00	7.00	10.00	11.00	13.00	17.00	18.00	19.00
28	1.00	5.00	6.00	10.00	10.00	9.00	17.00	18.00	17.00
29	9.00	10.00	12.00	13.00	14.00	16.00	16.00	16.00	70.00
30	7.00	8.00	14.00	15.00	16.00	16.00	18.00	17.00	18.00
31	7.00	7.00	10.00	8.00	7.00	10.00	14.00	14.00	14.00
32	1.00	1.00	8.00	7.00	9.00	10.00	11.00	11.00	15.00
33	1.00	6.00	10.00	13.00	12.00	15.00	13.00	15.00	14.00
34	3.00	3.00	5.00	7.00	7.00	9.00	10.00	11.00	11.00
35	2.00	7.00	7.00	12.00	9.00	12.00	15.00	14.00	15.00

Table 9. Job Ticket Difference Data

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*** RELEASE SIZES ***

WEEK	50.00	100.00	150.00	200.00	250.00	300.00	350.00	400.00	500.00
36	0.00	5.00	8.00	13.00	13.00	10.00	12.00	13.00	15.00
37	10.00	12.00	14.00	19.00	19.00	17.00	16.00	22.00	23.00
38	4.00	10.00	12.00	13.00	17.00	17.00	16.00	70.00	19.00
39	2.00	5.00	9.00	11.00	17.00	14.00	17.00	17.00	18.00
40	3.00	5.00	8.00	9.00	13.00	15.00	15.00	14.00	20.00
41	3.00	5.00	12.00	12.00	14.00	16.00	17.00	16.00	18.00
42	6.00	7.00	6.00	9.00	9.00	10.00	14.00	16.00	19.00
43	2.00	5.00	10.00	10.00	13.00	18.00	14.00	14.00	17.00
44	2.00	5.00	8.00	10.00	16.00	16.00	20.00	19.00	19.00
45			8.00	10.00	13.00	14.00	14.00	19.00	22.00

Table 9 (Continued)

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tickets observed. This type of analysis has been suggested as an appropriate analysis methodology for problems of this type, that is, problems in which one is trying to determine the best policy from several suggested policies. Sufficient data was not available to quantify the seasonality in orders; however, discussions with operating personnel confirmed the seasonality suggested by the plots of the data. Seasonality and any other non-random variations in the data are eliminated by studying the differences between the data observed for each level of the decision rule.

In the solution of this problem, the long term reduction in the job tickets issuance rate which would be expected under the various levels of the decision rule is required. It is thus necessary to use the time series data generated by the simulation model to determine the rates. The first step taken was to graphically display the data and from this visual display of data select an appropriate model to fit to the data. This data is graphed in Figures 43-45.

The form of the data suggests that an appropriate model would be one which would be curvilinear and rising quite rapidly approaching an asymtote. A modified exponential model of the form:

$$Y = a + br^t$$
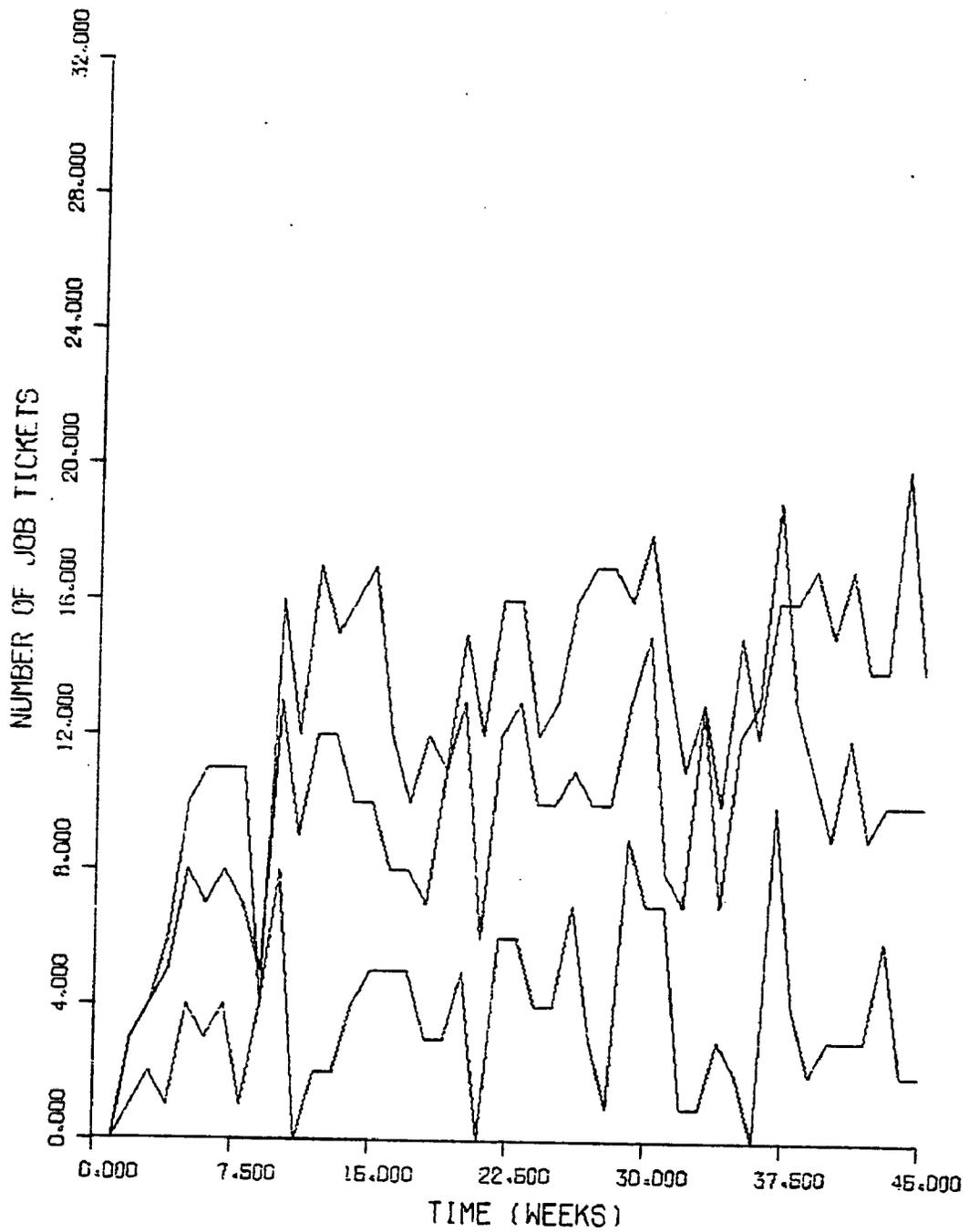
Figure 43. Plot of Job Ticket Difference Data (50, 200, 350)
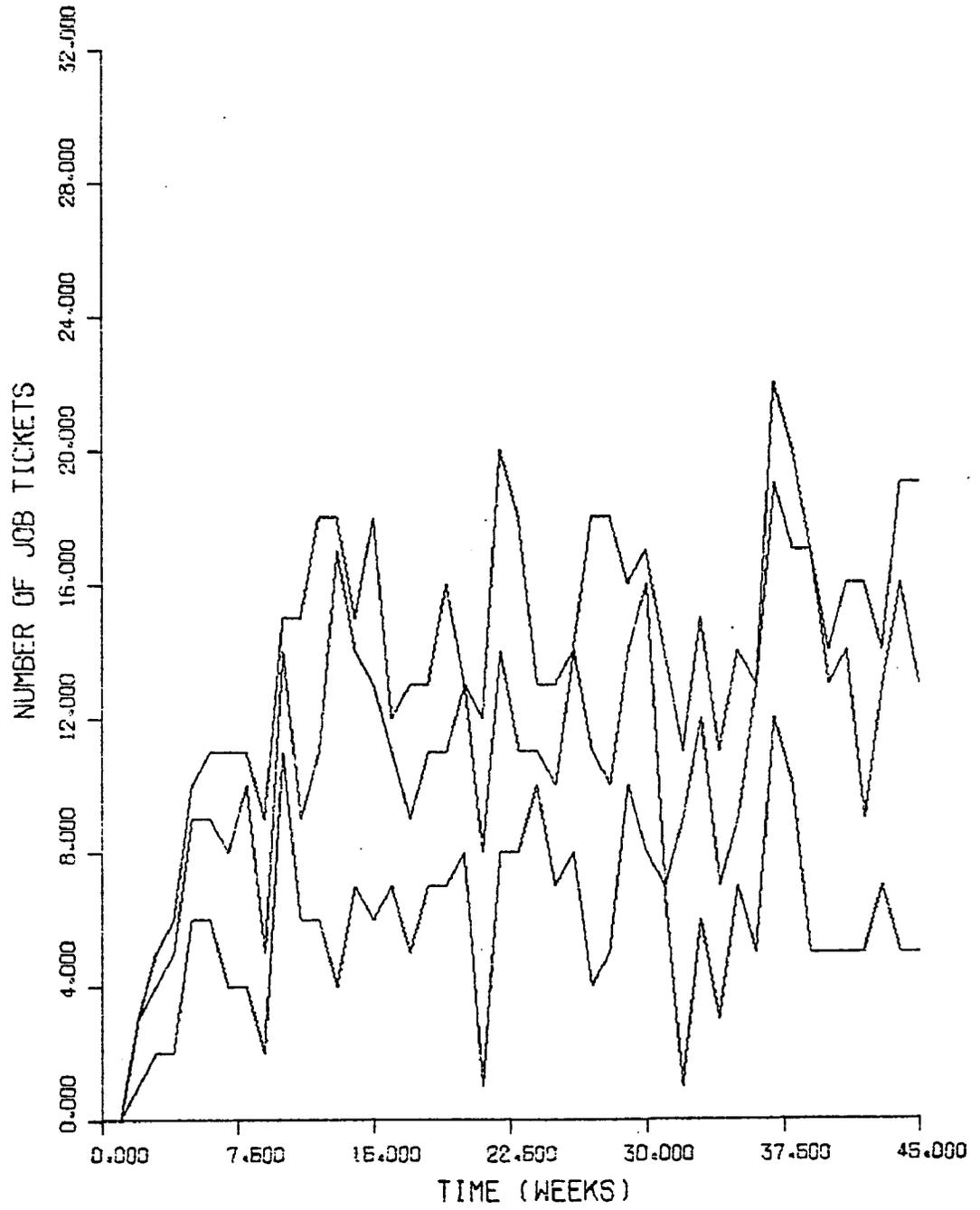
Figure 44.   Plot of Job Ticket Difference Data
             (100, 250, 400)

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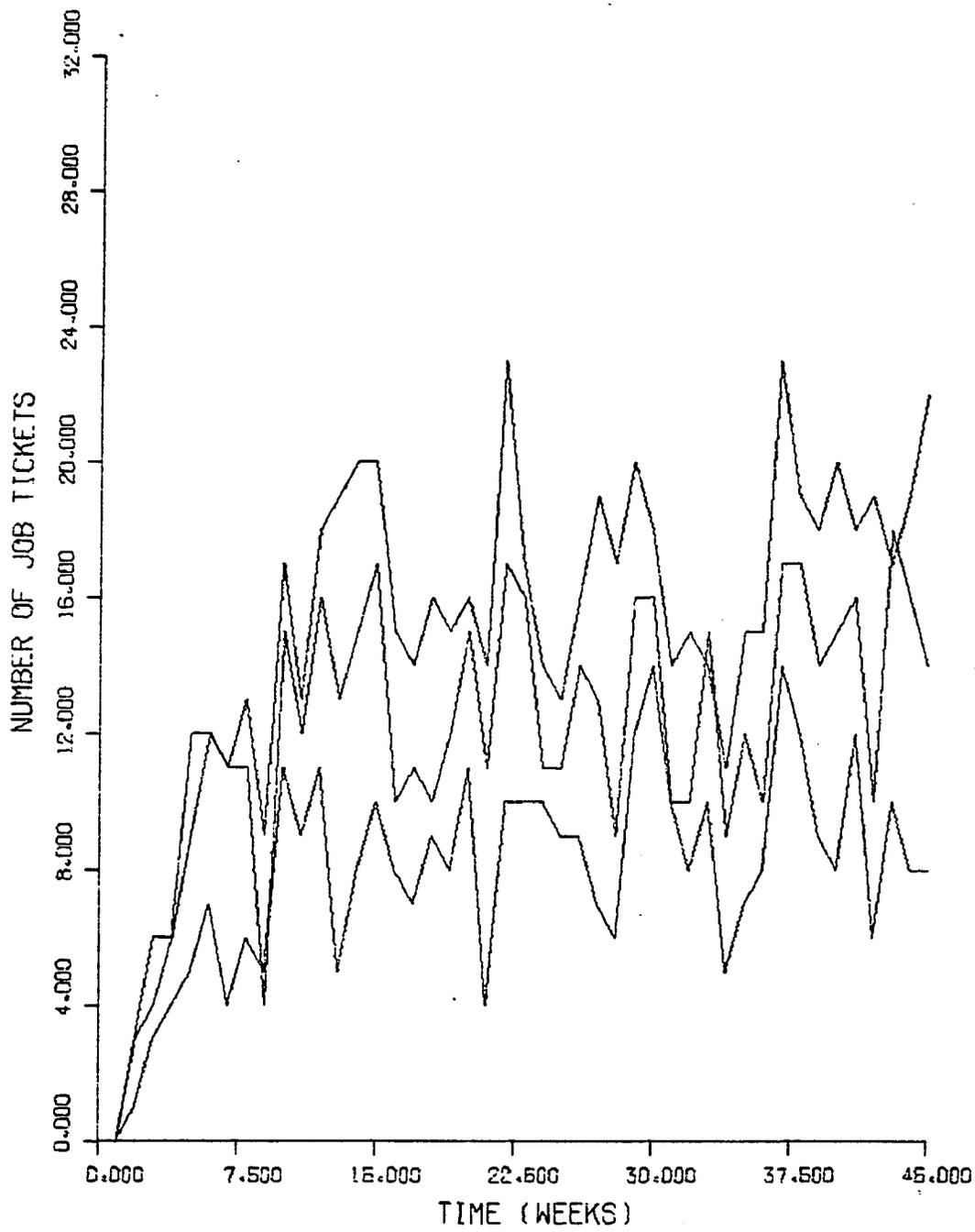
Figure 45. Plot of Job Ticket Difference Data
(150, 300, 500)

where

Y = job ticket difference

t = time period

r, a, b = appropriate least squares fitting constants

was fit to the individual job ticket data difference curves using the BMD non-linear regression program (99) available at the Lehigh University Computing Center. From the curves fit to the individual data, an appropriate r for the family of curves was determined by using the LEAPS linear regression program (100) available at Lehigh to search for the best fit over the range of r indicated by the non-linear results. The results of this search are shown in Table 10. Using Table 10, r = .79 was selected to be the name for this family of curves on the basis of standard error of the estimate. The low $\overline{R}$ values indicate that this model does not explain a large portion of the variation observed in the data on a weekly basis.

The job ticket difference data obtained from the simulation reaches steady state conditions relatively quickly; this can be observed from the plots of the data and the low value of r. To further investigate these steady state conditions a linear regression on the last twenty-five data points for each level of the decision rule were run, again using the LEAPS (100) program. The

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	50	100	150	200	250	300	350	400	500
r = .74									
Asymtote	3.84	6.32	8.83	10.59	12.08	13.30	14.35	15.40	16.85
Std. Error	2.3385	2.3408	2.2571	2.4847	2.8905	2.8332	2.6630	2.6983	2.8932
Durbin-Watson	2.125	2.066	2.002	1.840	1.629	2.087	1.762	1.419	1.404
$\bar{R}^2$	.01	.08	.22	.23	.23	.28	.38	.42	.43
r = .76									
Asymtote	3.85	6.36	8.80	10.64	12.15	13.37	14.44	15.49	16.95
Std. Error	2.3385	2.3390	2.2400	2.4694	2.8742	2.8226	2.6327	2.6663	2.8540
Durbin-Watson	2.126	2.068	2.030	1.862	1.646	2.100	1.797	1.446	1.436
$\bar{R}^2$	.01	.08	.23	.23	.23	.28	.38	.43	.44
r = .78									
Asymtote	3.88	6.40	8.95	10.71	12.23	13.45	14.54	15.59	17.07
Std. Error	2.3390	2.3392	2.2253	2.4570	2.8623	2.8186	2.6090	2.6435	2.8244
Durbin-Watson	2.125	2.067	2.053	1.881	1.658	2.104	1.827	1.467	1.461
$\bar{R}^2$	.01	.08	.24	.24	.24	.29	.39	.43	.44
r = .79									
Asymtote	3.89	6.42	8.99	10.75	12.27	13.50	14.59	15.65	17.13
Std. Error	2.3395	2.3400	2.2196	2.4521	2.8584	2.8195	2.6002	2.6364	2.8142
Durbin-Watson	2.124	2.065	2.062	1.888	1.663	2.103	1.838	1.473	1.470
$\bar{R}^2$	.01	.08	.24	.24	.24	.29	.40	.44	.45

Table 10. Search for Value of r in Modified Exponential
Model for Job Ticket Data

	50	100	150	200	250	300	350	400	500
Asymtote	3.90	6.44	9.02	10.79	12.32	13.55	14.65	15.71	17.20
Std. Error	2.3403	2.3422	2.2150	2.4482	2.5860	2.8227	2.5939	2.6327	2.8076
Durbin-Watson	2.123	2.062	2.070	1.895	1.665	2.098	1.846	1.476	1.476
$\bar{R}^2$	.01	.08	.25	.24	.24	.29	.40	.44	.46
Asymtote	3.93	6.49	9.11	10.88	12.42	13.65	14.78	15.85	17.35
Std. Error	2.3426	2.3484	2.2103	2.4444	2.8567	2.8364	2.5901	2.6369	2.8072
Durbin-Watson	2.119	2.051	2.077	1.902	1.665	2.079	1.851	1.4070	1.475
$\bar{R}^2$	.01	.08	.26	.24	.24	.28	.41	.44	.46
Asymtote	3.96	6.55	9.21	10.99	12.55	13.78	14.94	16.01	17.53
Std. Error	2.3462	2.3589	2.2126	2.4469	2.8656	2.8615	2.6005	2.6595	2.8272
Durbin-Watson	2.113	2.033	2.073	1.901	1.656	2.045	1.837	1.447	1.455
$\bar{R}^2$	.01	.08	.26	.24	.24	.27	.40	.43	.45

$r = .80$

$r = .82$

$r = .84$

Table 10 (Cont.)

results of these runs are shown in Table 11. This analysis indicates that steady state has been reached in twenty (20) simulated weeks as the standard deviation of the data and the standard error of the estimate of the first order regressions are not significantly different and the slopes of the first order regressions are not significantly different from zero.

The long term job ticket reductions under the modified exponential ($r = .79$) and zero degree regression models can be compared using a 250 day year. Table 12 contains this comparison data and shows that little difference in the estimates of the yearly reductions in job tickets by the two methods.

The long term estimates of the reduction in job tickets under the various levels of the decision rule must be translated into the cost reductions which will occur as a result of the rule usage. Since each job ticket is for a single component and each component undergoes some setup, the reduction in set-up cost is calculated as the product of the number of setups (job ticket) eliminated via the decision rule and the average cost of a setup.

The set-up cost reduction that can be expected due to the elimination of one job ticket was estimated via sampling. A sample of one-hundred (100) finished goods

Minimum Release Size	Mean	Standard Deviation	Standard Error of Mean	Intercept	Slope	Standard Error of Regression Coefficient	Standard Error of Estimate
50	3.84	2.734	.547	4.650	-.062	.074	2.753
100	6.28	2.685	.537	6.730	-.035	.076	2.731
150	9.04	2.541	.508	8.740	.023	.072	2.590
200	10.92	2.768	.553	10.55	.038	.078	2.819
250	12.20	3.175	.635	10.40	.138	.085	3.072
300	13.48	2.917	.583	12.30	.091	.080	2.901
350	14.84	2.375	.475	14.14	.053	.066	2.392
400	15.76	2.976	.595	14.75	.077	.083	2.985
500	17.20	3.122	.625	15.50	.131	.084	3.034

Table 11. Zero and First Order Linear Regression Results for the Last 25 Points of Job Ticket Difference Data

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Minimum Release Size	Estimated Weekly Reduction in Job Tickets		Standard Deviation of Weekly Reduction (S)		Projected Yearly Reduction in Job Tickets		Standard Error of Yearly Reduction Assuming $S = \sigma$	
	Modified Exp.	Zero Order Reg.	Modified Exp.	Zero Order Reg.	Modified Exp.	Zero Order Reg.	Modified Exp.	Zero Order Reg.
50	3.89	3.84	2.339	2.734	194	192	.331	.387
100	6.42	6.28	2.340	2.685	321	314	.331	.380
150	8.99	9.04	2.220	2.541	450	452	.314	.360
200	10.75	10.92	2.452	2.768	537	546	.347	.391
250	12.27	12.20	2.858	3.175	613	610	.404	.450
300	13.50	13.48	2.820	2.917	675	674	.399	.412
350	14.59	14.84	2.600	2.375	730	742	.368	.336
400	15.65	15.76	2.636	2.976	783	789	.373	.420
500	17.13	17.20	2.814	3.122	857	860	.398	.442

Table 12. Comparison of Modified Exponential and Regression Estimates of Job Ticket Reduction

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were selected by randomly entering a list of finished goods ordered during the year and determining the components required to assembly the finished goods by accessing the bill of materials. The routing of each component was used to determine the machines used (and setup) in the manufacture of the component. For each machine, the percentage of components whose manufacturing sequence requires the machine was determined. A sample of the finished goods items that are not inventoried was taken to determine if the machine usages were different from those of the entire group; a sample of thirty-five (35) items was used and only a few machine usage rates were different; the non-inventoried items were manufactured on hand equipment rather than automatic equipment for several operations.

The set-up times for each component on the machines are sequence dependent; that is, the set-up time for a component is dependent upon the component which preceded it on the machine. The shop practice is to group the items so that the amount of setup is minimized. The set-up time is thus composed of two parts, a base charge which is incurred when a new group is set up and an adjustment charge for each additional ticket processed on the setup. In view of the current shop practice, a reduction of one job ticket will only eliminate the adjustment

charges for the component on the machine(s); it will not impact on the base charge. The data used to estimate the average set-up time is summarized in Table 13. Applying the cost of set-up labor to the projected long term reduction in job tickets (from Table 10, $r = .79$) the annual set-up cost reduction under the various levels of the decision rule are determined and are displayed in Table 14.

Opera-tion	Set-up Time Base (Min)	Set-up Time Per Ticket (Min)	Usage Rate for non-inventoried items (Percent)	Usage Rate Overall (Percent)	Time Saved by one Ticket Reduction (Min)
40-A	20	5	100	100	5.00
47-A	0	0	100	100	.00
111-A	15	5	92	92	4.60
146-A	0	0	92	92	.00
88-A	10	3	92	92	2.76
735-A	10	3	92	92	2.76
158-A	90	10	74	74	7.40
158-B	90	10	62	57	6.20
158-C	90	10	6	13	.60
158-D	90	10	2	1	.20
72-A	0	5	4	8	.20
76-A	10	3	30	17	1.90
725-A	10	3	4	6	.12
649-A	10	3	9	5	.27
102-A	10	3	9	10	.27
104-C	10	5	85	58	4.25
104-B	45	5	23	17	1.15
79-A	40	6	28	20	1.68
79-B	40	6	28	20	1.68
79-C	40	6	26	21	1.56
79-D	40	6	30	22	1.80
80-A	20	5	28	23	1.40
663-A	10	3	2	3	.06
620-A	10	0	2	4	.00
733-A	10	3	2	3	.06
107-G	30	1.5	53	54	.80
143-A	20	0	34	21	.00
675-A	0	5	2	1	.10
154-A	50	3	2	1	.06
154-C	50	3	4	2	.12
154-Q	50	3	9	2	.27
160-A	20	10	26	26	2.60
160-B	20	10	26	26	2.60
737-A	0	0	2	2	.00
648-A	10	3	21	9	.63
45-A	25	5	4	1	.20
730-A	10	5	4	1	.20
101-A	0	30	4	1	1.20
159-A	40	6	6	3	.36
719-A	0	0	4	3	.00

Total   55.06

Table 13. Set-up Time Estimate Data

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Minimum Manufacturing Lot Size	Annual Reduction in Job Tickets	Reduction in Hrs. of Setup Required (Hrs)	Cost Savings at Regular Time Rate ($)	Cost Savings if Setup Performed in Overtime ($)
50	192	176	1032	1548
100	314	288	1690	2535
150	452	415	2435	3653
200	546	501	2940	4410
250	610	560	3286	4929
300	674	618	3626	5439
350	742	681	4354	6531
400	789	724	4248	6372
500	860	789	4630	6945

Table 14.   Annual Set-up Cost Savings

4.3 Inventory Data

The inventory analysis is conducted for each item of inventory, that is, for the finished goods, component, manufacturing-in-process, and assembly-in-process inventories. This is one to facilitate observation of the effect that the introduction of a minimum manufacturing lot size decision rule would have upon each type of inventory.

Since the additional components manufactured under the decision rule are stored in component inventory, the finished goods inventory level should be insensitive to the level of the decision rule being tested. As can be seen from the observed data (Table 15) and a plot (Figure 46) of the data for the ten release sizes of the rule under test, almost no variation was observed between the finished good inventory levels.

As mentioned above, the additional components manufactured as a result of adherence to a minimum manufacturing lot size decision rule are stored in component inventory. This practice will have two advantages over complete processing of the components into finished goods; flexibility will be increased as the stored components can be assembled into a different finished goods in response to orders and the total valuation of inventory will be reduced, reducing investment and taxes.

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*** RELEASE SIZES ***

WEEK	0.00	50.00	100.00	150.00	200.00	250.00	300.00	350.00	400.00	500.00
1	499582.25	499582.25	499582.25	499582.25	499582.25	499582.25	499582.25	499582.25	499582.25	499582.25
2	491861.13	491861.13	491861.13	491861.13	491861.13	491861.13	491861.13	491861.13	491861.13	491861.13
3	479006.44	479006.44	479006.44	479006.44	479006.44	479006.44	479006.44	479006.44	479006.44	479006.44
4	464858.63	464858.63	464858.63	464858.63	464858.63	464858.63	464858.63	464858.63	464858.63	464858.63
5	471122.44	471122.44	471122.44	471122.44	471122.44	471122.44	471122.44	471122.44	471122.44	471122.44
6	478692.06	478692.06	478692.06	478692.06	478692.06	478692.06	478692.06	478692.06	478692.06	478692.06
7	479785.38	479785.38	479785.38	479785.38	479785.38	479785.38	479785.38	479785.38	479785.38	479785.38
8	488913.31	488913.31	488913.31	488913.31	488913.31	488913.31	488913.31	488913.31	488913.31	488913.31
9	503836.56	503836.56	503836.56	503836.56	503836.56	503836.56	503836.56	503874.00	503893.75	503904.06
10	503155.63	503155.63	503155.63	503155.63	503155.63	503155.63	503155.63	503193.06	503212.81	503317.63
11	501322.50	501322.50	501322.50	501322.50	501322.50	501322.50	501322.50	501359.94	501379.69	501484.50
12	502649.31	502649.31	502649.31	502649.31	502649.31	502649.31	502643.31	502649.31	502649.31	502663.75
13	505044.88	505044.88	505044.88	505092.13	505092.13	505092.13	505105.25	505105.25	505092.13	505193.81
14	501246.44	501246.44	501246.44	501293.69	501332.75	501334.25	501347.38	501347.38	501347.38	501421.44
15	494648.88	494648.88	494648.88	494696.13	494735.19	494736.69	494749.81	494749.81	494749.81	494833.88
16	494146.63	494146.63	494146.63	494146.69	494185.75	494187.25	494187.25	494187.25	494187.25	494187.19
17	487631.75	487631.75	487631.75	487631.56	487631.75	487631.75	487631.88	487631.88	487631.88	487676.75
18	490986.75	490986.75	490986.75	490986.81	491031.88	491022.75	491032.00	491066.88	491108.75	491185.63
19	481137.94	481137.94	481137.94	481138.00	481137.94	481137.94	481138.06	481209.63	481308.81	481434.44
20	486836.25	486836.25	486836.25	486836.31	486836.25	486872.25	486836.38	486907.94	487007.13	487132.75
21	489823.19	489823.19	489823.19	489823.25	489840.13	489840.25	489840.25	489876.88	489931.19	489937.81
22	485398.68	485398.68	485398.88	485398.94	485415.81	485477.56	485491.69	485552.88	485618.75	485622.13
23	487357.50	487357.50	487357.50	487351.56	487374.44	487436.19	487450.31	487528.19	487554.25	487540.94
24	485892.94	485892.94	485892.94	485893.00	485909.88	485971.63	485985.75	486063.63	486089.69	486076.38
25	483103.44	483113.44	483103.44	483103.50	483103.44	483198.63	483218.69	483296.56	483322.63	483303.25
26	491298.44	491298.44	491298.44	491298.50	491298.44	491332.00	491337.94	491354.50	491354.69	491360.31
27	492080.19	492080.19	492080.19	492080.25	492080.19	492113.75	492119.69	492136.25	492136.44	492142.06
28	498624.75	498624.75	498624.75	498624.81	498624.75	498649.38	498661.19	498688.69	498688.88	498698.00
29	497091.38	497091.38	497091.38	497091.44	497091.38	497116.00	497127.81	497155.31	497155.50	497064.69
30	493441.25	493441.25	493441.25	493449.06	493449.00	493473.63	493495.69	493523.19	493523.38	493506.50
31	496479.38	496479.38	496479.38	496528.63	496508.56	496508.56	496624.50	496654.06	496654.25	496659.44
32	493464.69	493464.69	493464.69	493513.94	493493.88	493493.88	493609.81	493702.81	493709.69	493657.19
33	488806.88	488806.88	488806.88	488848.38	488828.31	488828.31	488934.00	489027.00	489066.94	489019.25
34	493201.31	493201.31	493201.31	493242.81	493201.31	493201.31	493307.00	493462.44	493528.00	493600.38
35	491041.69	491041.69	491041.69	491041.69	491041.69	491041.69	491041.75	491133.31	491193.13	491301.44

Table 15.   Finished Goods Inventory Level Data

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*** RELEASE SIZES ***

WEEK #	0.00	50.00	100.00	150.00	200.00	250.00	300.00	350.00	400.00	500.00
36	493493.94	493493.94	493493.94	493494.00	493493.94	493493.88	493493.94	493573.00	493599.75	493807.81
37	495183.38	495183.38	495183.38	495183.44	495233.38	495233.31	495183.38	495301.50	495336.31	495337.75
38	495552.00	495552.00	495552.00	495552.06	495602.00	495601.94	495552.00	495718.50	495762.88	495764.31
39	487552.13	487552.13	487552.13	487552.19	487602.13	487602.13	487552.13	487718.63	487763.00	487659.94
40	486699.50	486699.50	486699.50	486699.63	486865.06	486780.50	486860.75	486931.50	486941.44	486848.06
41	488212.94	488212.94	488212.94	488213.06	488378.50	488293.94	488374.19	488396.56	488396.88	488362.50
42	477212.19	477212.19	477212.19	477212.31	477377.75	477293.19	477373.44	477395.81	477438.50	477361.75
43	470970.44	470970.44	470970.44	470970.50	471056.63	470982.63	471069.88	471111.94	471129.06	471042.63
44	473076.94	473076.94	473076.94	473102.50	473163.13	473089.13	473176.38	473218.44	473235.36	473090.25
45	467719.63	467719.63	467719.63	467745.19	467805.81	467731.81	467890.69	467956.56	467872.44	467769.63

Table 15 (Continued)
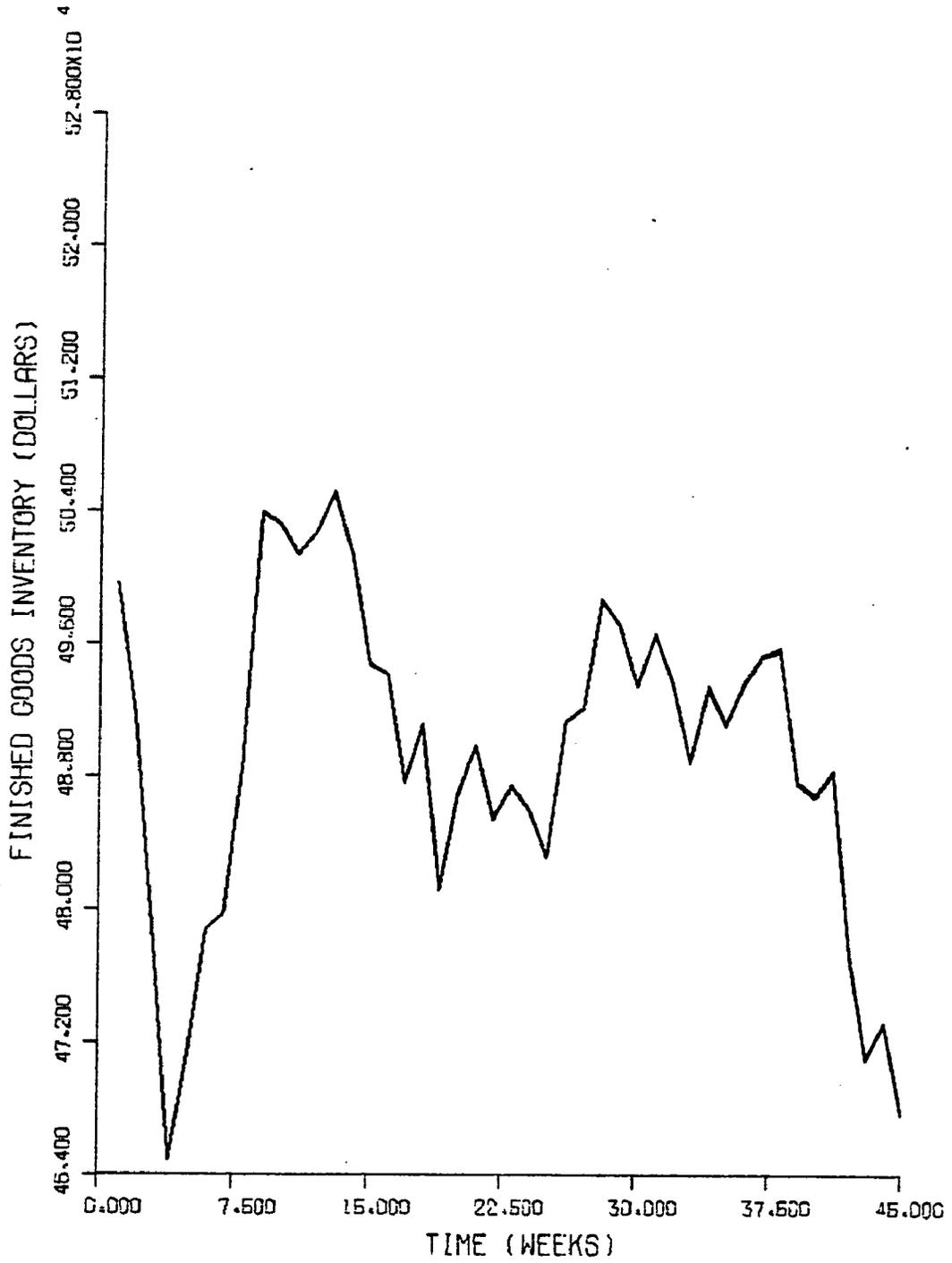
Figure 46. Plot of Finished Goods Inventory Data

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Under current practice, no component inventory is kept; therefore, the effect of the decision rule upon component inventory is easily observed. The observed values of the component inventory for the simulation are shown in Table 16 and graphed in Figure 47. The variation in sales over time has an effect upon the component inventory; to isolate the effect of the decision rule on the inventory from the sales effect, the difference in the component inventory level for the base (zero) manufacturing lot size rule and the higher levels of the decision rule were calculated. These differences are shown in Table 17 and plotted in Figure 48. The form of the graphs suggest that a curvilinear model which rises and approaches an asymtote may yield the best fit.

A number of curvilinear models were fit to the data and the modified exponential model yielded the best fit. As in the analysis of the job ticket data, the analysis was conducted in two steps; first the BMD non-linear regression program (99) was used to determine the best unrestricted fit for each of the difference curves for the model; then the LEAPS linear regression program was used to find the best r for the family of curves. The range of r evaluated and the results for the various values of r tested are shown in Table 18.

*** RELEASE SIZES ***

WEEK #	0.00	50.00	100.00	150.00	200.00	250.00	300.00	350.00	400.00	500.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	880.66	990.97	1322.93	1861.56	2318.93	3230.35	4138.65	5108.48	6074.41	8069.92
5	1376.17	1555.43	2138.66	3050.07	3569.54	4652.81	5781.91	7107.77	8439.09	11248.07
6	2045.92	2335.97	3122.66	4448.36	5351.19	6922.80	8557.04	10454.32	12332.76	16176.19
7	1747.28	2099.88	2987.18	4472.26	5528.24	7270.00	9027.23	11006.18	12926.59	17378.08
8	2531.66	3052.33	4414.36	6625.93	7481.43	9976.94	11699.89	14099.89	16488.65	21643.65
9	3107.71	3659.28	5019.81	7232.75	8205.31	10750.14	12449.43	14951.54	17294.43	22600.18
10	4366.36	4939.80	6247.00	8958.35	9887.54	12617.86	15289.35	18417.29	21464.39	25112.69
11	5792.97	6453.14	7783.37	10750.45	12222.51	15176.92	18202.17	21803.72	25267.78	29915.23
12	6396.73	7259.68	8874.75	11957.23	14049.60	17436.65	21119.10	25384.35	29113.25	35004.99
13	8580.46	9517.26	11271.43	14578.22	16817.74	20476.23	24342.54	28849.09	32892.65	39290.45
14	11176.96	12024.52	14016.67	16971.14	19244.48	22960.52	26708.59	31223.66	34475.07	42101.71
15	14432.90	15405.59	17657.01	20224.41	23319.52	26430.44	30083.48	34720.47	38904.95	45979.01
16	11140.43	12170.09	14670.09	17551.65	20741.96	23896.36	28005.70	32817.77	37330.83	44807.53
17	8028.55	8985.04	11502.21	14710.18	18254.09	21578.80	25978.93	31216.23	36285.02	44411.06
18	8077.54	9113.31	11996.80	15546.06	19613.54	23319.20	28060.31	33668.09	39208.18	48229.87
19	9887.93	10344.38	13672.54	17271.73	21505.15	25089.03	30213.88	35869.89	41369.77	50437.96
20	6854.40	7768.65	10668.28	14376.93	18705.94	22521.94	27656.17	33860.15	39373.86	48786.18
21	7118.87	8142.17	11123.89	14965.46	19402.30	23351.96	28623.45	34791.04	40444.27	49680.27
22	7504.91	8730.84	11528.91	15187.55	19355.68	23136.32	27974.96	34311.89	39664.83	49196.50
23	7058.28	8070.21	10671.52	14459.00	18149.85	22271.73	26537.49	32838.40	38497.51	48192.42
24	6551.22	7698.12	10305.96	14342.50	18296.29	22541.93	27012.54	33603.68	39628.96	50123.31
25	8027.80	9138.52	11689.12	15853.46	20277.31	25076.28	28703.49	35557.64	41407.17	51877.28
26	8729.99	9887.32	12751.96	17847.68	21257.97	27397.81	29973.35	37140.33	43239.27	56288.94
27	6743.13	7831.88	10491.09	15515.44	19042.20	25295.21	28008.69	35283.66	41013.45	54456.56
28	6976.64	8098.47	10756.56	15817.13	19375.57	25919.54	28933.89	36419.48	42642.27	57078.25
29	7817.47	8970.11	11893.15	16888.29	20814.53	27366.61	30390.01	38035.91	45633.03	60423.94
30	9215.16	10319.08	13344.43	18386.14	22358.91	29179.07	32158.07	39751.13	47392.13	62252.34
31	8585.04	9832.23	12982.07	18592.45	22796.13	29885.49	33339.11	39219.29	46969.48	62953.26
32	8538.60	9771.13	12906.65	18302.39	22516.85	29645.60	32899.24	39244.68	46770.88	62829.07
33	6637.69	7903.04	11122.38	16439.61	20476.65	27648.43	30948.69	37340.63	45103.05	61492.48
34	7288.70	8549.85	11816.18	17088.18	21310.63	28706.50	32010.06	38441.05	46349.98	63313.34
35	7442.20	8818.80	12375.76	17295.38	22495.00	29416.23	32625.57	39308.95	47698.95	64591.62

Table 16. Component Inventory Level Data

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*** RELEASE SIZES ***

WEEK #	0.00	50.00	100.00	150.00	200.00	250.00	300.00	350.00	400.00	500.00
36	7612.04	9074.30	12649.04	17483.05	22556.73	29527.39	32836.03	39795.73	47912.08	65292.86
37	7351.23	8813.79	12425.44	17260.39	22289.79	29493.65	32777.41	39660.19	47777.77	65361.25
38	7736.74	9268.05	12904.95	17795.67	23003.54	30223.30	34063.34	40641.99	48905.27	67345.69
39	6835.52	8258.82	11825.55	16635.46	21606.42	28639.12	32930.59	39846.38	47922.42	65217.37
40	7790.65	9194.57	12797.79	17489.73	22640.61	29367.51	33076.16	41337.37	48923.16	65954.81
41	8087.73	9699.84	13426.68	18685.82	24020.71	30117.24	35748.01	42234.25	49424.13	66814.44
42	7594.85	9118.80	13080.33	18350.24	23668.08	29482.96	35690.58	42136.98	49669.91	67566.19
43	10289.13	11717.54	15664.92	21137.34	26576.11	32160.28	38431.25	45100.52	52923.72	70543.13
44	10461.64	11920.72	15858.14	21543.55	27027.65	32818.82	38757.06	45759.97	53632.87	71322.63
45	9170.85	10505.71	14339.59	20182.91	25542.90	31241.48	37338.61	43414.32	51321.79	68320.25

Table 16 (Continued)

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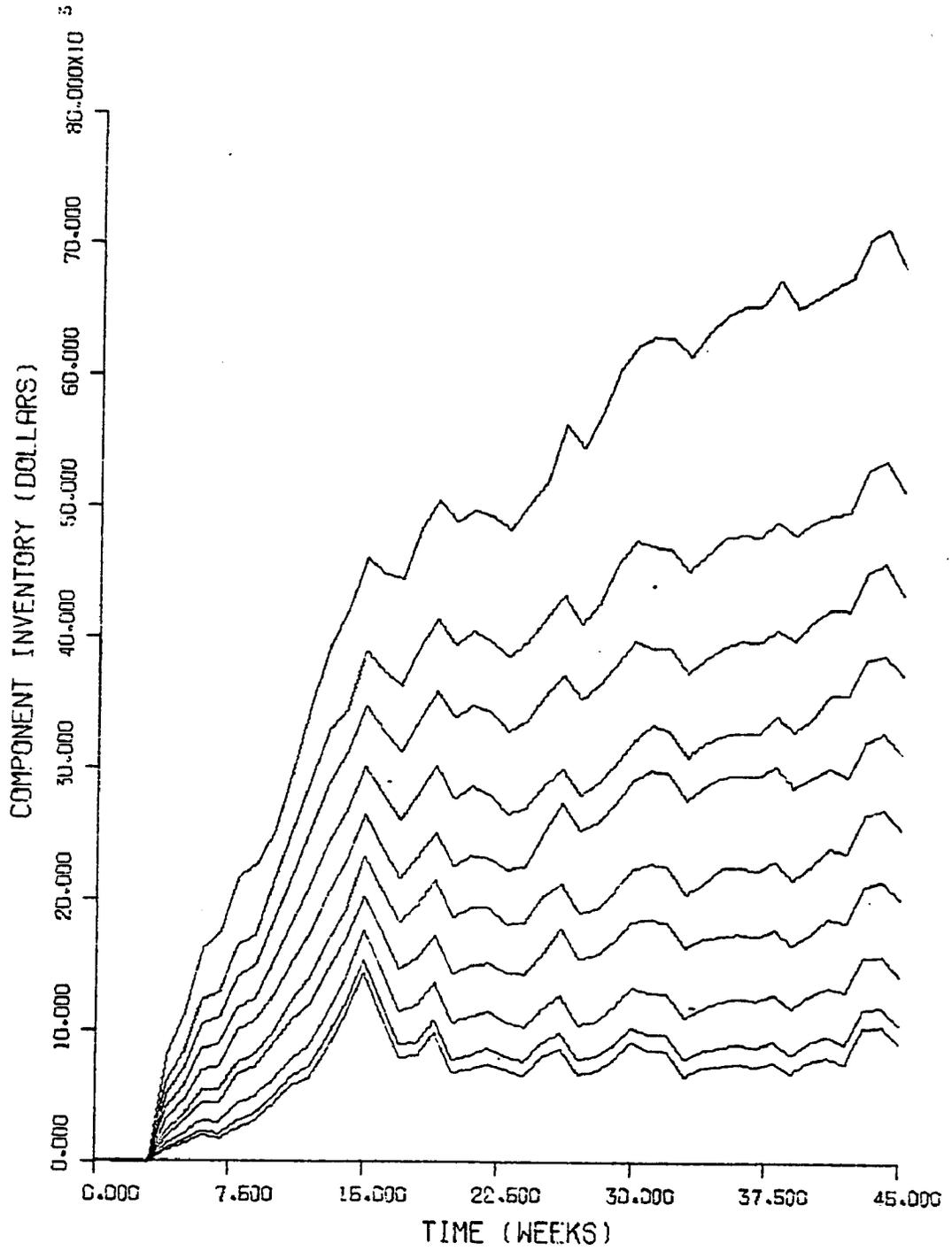
Figure 47. Plot of Component Inventory Data

*** RELEASE SIZES ***

* WEEK *	50.00	100.00	150.00	200.00	250.00	300.00	350.00	400.00	500.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	110.31	442.27	980.90	1438.27	2349.69	3257.99	4227.82	5193.75	7189.26
5	219.26	762.49	1673.90	2193.37	3276.64	4405.74	5731.60	7062.92	9671.90
6	290.05	1076.74	2402.44	3305.27	4876.88	6511.12	8408.40	10286.84	14130.27
7	352.60	1239.90	2724.98	3780.96	5522.72	7279.95	9256.80	11179.31	15610.80
8	520.67	1882.70	4094.27	4949.77	7445.28	9164.27	11568.23	13956.99	19111.99
9	551.57	1912.10	4125.04	5097.60	7642.43	9341.72	11843.83	14186.72	19492.47
10	573.44	1880.64	4591.99	5521.18	8251.50	10922.99	14050.93	17098.03	20746.33
11	660.17	1990.40	4957.48	6429.54	9383.95	12409.20	16010.75	19474.81	24122.26
12	862.95	2478.02	5560.50	7652.87	11039.92	14722.37	18987.62	22716.52	28600.26
13	936.80	2690.97	5997.76	8237.28	11895.77	15762.08	20268.63	24312.19	30709.99
14	847.56	2839.71	5794.18	8067.52	11783.56	15531.63	20051.70	23298.11	30924.75
15	972.69	3224.11	5791.51	8886.62	12047.54	15650.58	20287.57	24472.05	31546.11
16	1029.59	3529.66	6411.22	9601.53	12755.93	16865.27	21677.34	26190.40	33667.10
17	956.49	3473.66	6681.63	10225.54	13550.25	17950.38	23187.68	28256.47	36382.51
18	1025.77	3919.26	7468.52	11541.00	15241.66	19982.77	25590.55	31130.64	40152.33
19	956.45	3784.61	7383.85	11617.22	15201.10	20325.95	25981.96	31481.84	40550.03
20	914.25	3813.88	7522.53	11851.54	15667.54	20801.77	27005.75	32519.46	41931.78
21	1023.30	4005.02	7846.59	12283.43	16233.09	21504.58	27672.17	33325.40	42561.40
22	1225.93	4024.00	7682.64	11850.77	15631.41	20470.05	26806.98	32159.92	41691.59
23	1011.93	3613.24	7400.72	11091.57	15213.45	19479.21	25780.12	31439.23	41134.14
24	1146.90	3754.74	7791.28	11745.07	15990.71	20461.32	27052.46	33077.74	43572.09
25	1110.72	3661.32	7825.66	12249.51	17048.48	20675.69	27529.84	33379.37	43849.48
26	1157.33	4021.97	9117.69	12527.98	18667.82	21243.36	28410.34	34509.29	47558.95
27	1088.75	3747.96	8772.31	12259.07	18552.08	21265.56	28540.53	34270.32	47713.43
28	1121.83	3779.92	8840.49	12398.93	18942.90	21957.25	29442.84	35665.63	50101.61
29	1152.64	4075.68	9070.82	12997.06	19549.14	22572.54	30218.44	37815.56	52606.47
30	1103.92	4129.27	9170.98	13143.75	19963.91	22942.91	30535.97	38176.97	53037.18
31	1247.19	4397.03	10007.41	14211.05	21300.45	24754.07	30634.25	38404.44	54368.22
32	1232.53	4368.05	9763.79	13978.25	21107.00	24360.64	30706.08	38232.28	54290.47
33	1265.35	4484.69	9801.92	13838.96	21010.74	24311.00	30702.94	38465.36	54854.79
34	1261.15	4527.48	9799.48	14021.93	21417.80	24721.36	31152.35	39061.29	56024.64
35	1376.60	4933.56	9853.18	15052.80	21974.03	25183.37	31866.75	40256.75	57149.42

Table 17. Component Inventory Difference Data

*** RELEASE SIZES ***

WEEK #	50.00	100.00	150.00	200.00	250.00	300.00	350.00	400.00	500.00
36	1462.26	5037.00	9871.01	14944.69	21915.35	25223.99	32183.69	40300.04	57680.82
37	1462.56	5074.21	9909.16	14938.56	22142.42	25426.18	32308.96	40426.56	58010.02
38	1531.31	5168.21	10058.93	15266.80	22486.56	26326.60	32905.25	41168.53	59608.95
39	1423.30	4990.03	9799.94	14770.90	21803.60	26095.07	33010.86	41086.90	58381.85
40	1403.92	5007.14	9699.08	14849.96	21596.86	26085.51	33546.72	41132.51	58164.16
41	1612.11	5338.95	10598.09	15932.98	22029.51	27660.28	34146.52	41336.40	58726.71
42	1513.95	5485.48	10755.39	16073.27	21888.11	28095.73	34542.13	42075.06	59971.34
43	1428.41	5375.79	10848.21	16286.98	21871.15	28142.12	34811.39	42639.59	60254.00
44	1459.08	5396.50	11081.91	16566.01	22357.18	28295.42	35298.33	43171.23	60860.99
45	1414.86	5168.74	11012.06	16372.05	22070.63	28157.76	34243.47	42150.94	59149.40

Table 17 (Continued)

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r		50	100	150	200	250	300	350	400	500
$r = .93$	Asymtote	1473.1	5267.1	10838.9	16221.1	23183.1	27936.3	35580.1	43888.0	61420.5
	Std. Error	118.24	316.9	417.1	638.5	868.3	1072.4	892.9	1082.2	2360.1
	Durbin-Watson	1.15	.50	.90	.59	.46	.46	.69	1.02	.31
	$\bar{R}^2$	.79	.88	.96	.94	.96	.94	.98	.93	.96
$r = .94$	Asymtote	1537.3	5505.9	11319.1	16972.1	24270.9	29165.4	37093.7	45796.0	64337.5
	Std. Error	115.9	301.4	368.9	579.2	727.5	991.1	938.8	1055.3	1826.7
	Durbin-Watson	1.20	.55	1.16	.71	.64	.54	.63	1.08	.50
	$\bar{R}^2$	.80	.89	.96	.96	.97	.95	.97	.98	.97
$r = .945$	Asymtote	1578.2	5657.9	11624.4	17449.6	24961.6	29947.1	38055.5	47008.50	66190.9
	Std. Error	115.4	297.0	356.5	569.3	688.1	980.7	1017.4	1124.0	1613.3
	Durbin-Watson	1.21	.57	1.24	.73	.72	.55	.55	.96	.63
	$\bar{R}^2$	.80	.90	.96	.96	.97	.96	.97	.98	.98
$r = .9475$	Asymtote	1601.5	5744.8	11798.7	17722.4	25355.8	30393.7	38604.8	47700.8	67248.0
	Std. Error	115.3	295.8	353.9	570.0	678.9	984.1	1063.2	1176.9	1529.4
	Durbin-Watson	1.21	.57	1.26	.73	.74	.55	.50	.88	.70
	$\bar{R}^2$	.80	.90	.96	.96	.97	.96	.97	.97	.98
$r = .95$	Asymtote	1627.2	5840.4	11990.5	18022.4	25789.3	30885.0	39208.9	48467.0	68411.1
	Std. Error	115.3	295.2	353.9	574.6	677.3	993.3	1125.6	1240.4	1465.2
	Durbin-Watson	1.21	.57	1.27	.72	.75	.54	.47	.79	.76
	$\bar{R}^2$	.80	.90	.97	.96	.97	.95	.96	.97	.98
$r = .96$	Asymtote	1762.3	6342.4	12997.09	19597.1	28062.2	33464.6	42378.9	52455.7	74510.7
	Std. Error	116.7	299.9	379.8	630.7	748.1	1086.0	1404.7	1575.3	1459.3
	Durbin-Watson	1.19	.57	1.12	.61	.63	.47	.31	.51	.78
	$\bar{R}^2$	.80	.89	.96	.95	.97	.95	.94	.95	.98

Table 18. Search for r - Component Inventory Dfference Data

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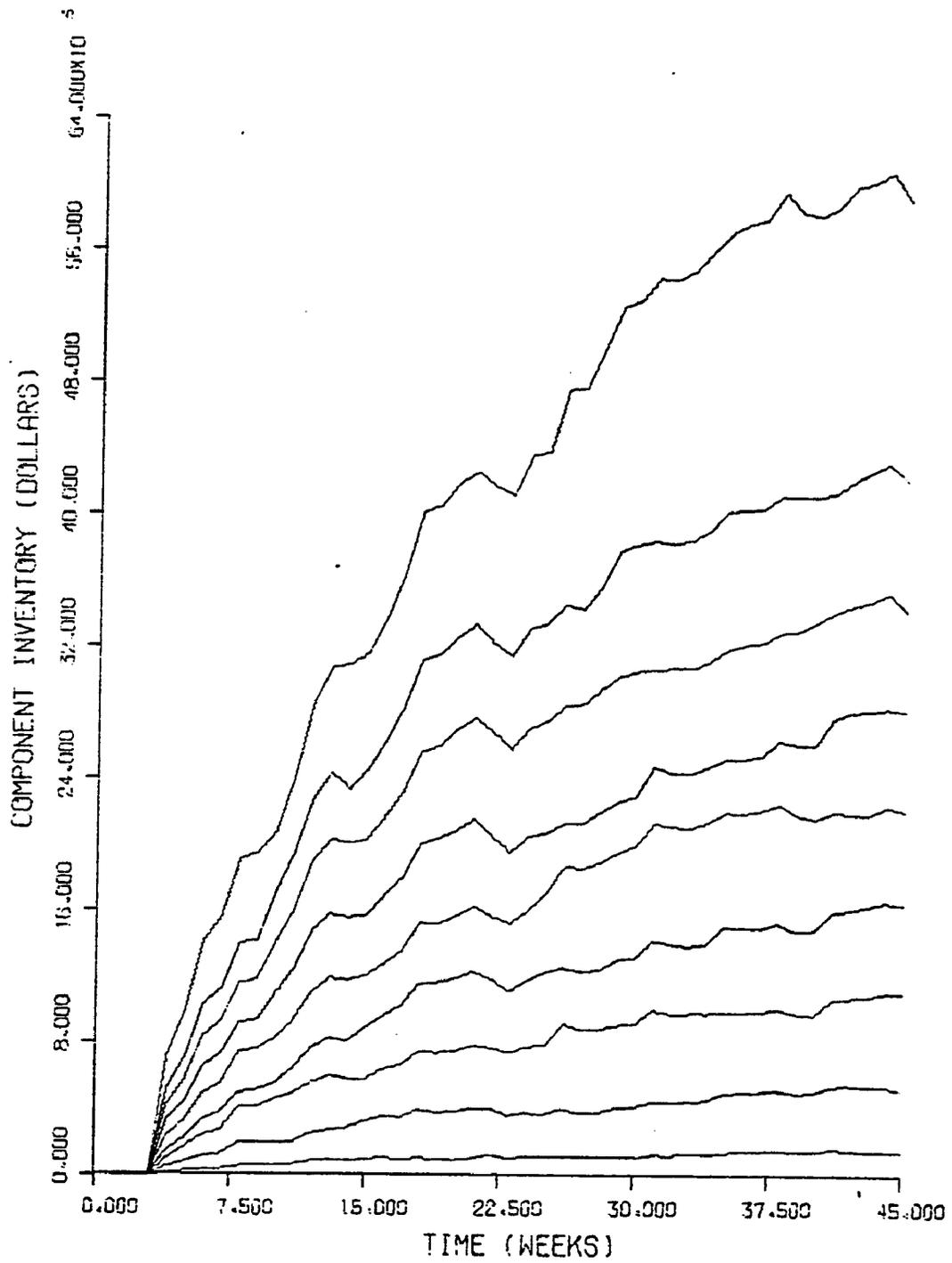
Figure 48. Plot of Component Inventory Difference
Data

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An r value of .9475 was judged to yield the best fit
to the family of curves on the basis of the standard
errors of the estimate and $\overline{R}^2$. The low Durbin-Watson
statistics indicate the presence of autocorrelation in
the residuals. The data, however, is from a cumulative
phenomenon and Feller (5) has observed this type of
autocorrelation in this work on the theory of cumulative
processes in ballot problems and random walk (coin-
flipping) experiments and shown that the autocorrelation
pattern of the residuals of the type observed in the
inventory data is not expected when measuring cumulative
phenomenon when the observations are independent. Feller's
work has shown that the autocorrelation of the residuals
is not an impediment to the use of tests of significance
which assume independent observations. In order to
further test if the autocorrelation of residuals can be
ignored, the derivative of the modified exponential model
is determined and its value and the observed rate of
change in the data between successive points compared.
The residuals observed for this data are randomly dis-
tributed as shown by the Durbin-Watson statistics for
this test as shown in Table 19. Since the derivative of
the model used and the observed slopes have reasonably
randomly distributed residuals and the model is of the
type for which autocorrelation is not unexpected, it is

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Min Release Size	Durbin-Watson Statistic
50	2.875
100	2.563
150	2.676
200	2.239
250	2.120
300	2.048
350	1.806
400	2.403
500	2.011

Table 19. Durbin-Watson Statistics for Residuals of Observed Slopes of Derivative of Model Used for Curve Fitting to the Family of Component Inventory Curves

concluded that the autocorrelation observed is not an impediment to the use of statistical tests of significance which assume that the observations are independent.

The manufacturing-in-process inventory is used to measure the level of activity in the manufacturing areas, or the load placed upon the facility. The level of the manufacturing-in-process inventory at the end of each scheduling period are listed in Table 20 and plotted in Figure 49. From these values, one observes that the differences between the observed inventory level for the various levels of the decision rule decreases or dampens out over time. This observation becomes more apparent if one observes the differences between the inventory at the higher levels and the zero level tabulated in Table 21 and plotted in Figure 50. This reduction in the difference in capacity requirements of the various levels of the decision rule is also shown by the number of pieces scheduled data shown in Tables 22 and 23 which are plotted in Figures 51 and 52.

The observed values for the assembly-in-process inventory are similar to those observed for the finished goods inventory in that the value of the inventory is insensitive to the various levels of the minimum manufacturing lot size decision rule. The observed values of the value of the assembly-in-process inventory are shown in Table 24 and plotted in Figure 53.

*** RELEASE SIZES ***

* WEEK *	0.00	50.00	100.00	150.00	200.00	250.00	300.00	350.00	400.00	500.00
1	12229.42	12313.92	12502.32	12835.20	13120.86	13640.43	14163.08	14706.51	15256.33	16374.52
2	21188.88	21331.89	21666.22	22228.19	22524.98	23252.58	23983.26	24743.62	25510.35	27120.00
3	28241.87	28425.72	28899.18	29689.69	30233.91	31251.66	32299.38	33372.92	34428.97	36620.65
4	27178.78	27329.77	27693.04	28713.92	28565.03	29199.97	29829.78	30541.93	31225.57	32665.99
5	34701.40	34882.20	35408.62	36127.52	36751.01	37521.98	37531.82	38239.52	38978.82	40350.68
6	31516.82	31707.48	32126.18	32683.38	33156.01	33690.89	33396.42	33954.16	34510.79	35474.29
7	24260.95	24428.73	24751.21	25532.01	25502.14	26021.50	26434.79	27061.50	27687.66	27444.20
8	15760.50	15924.77	15922.60	16481.54	16430.51	16713.16	17761.57	18437.07	19070.91	18819.30
9	17321.36	17502.77	17635.26	18247.38	18317.27	18799.21	20239.45	21099.52	21582.26	21807.96
10	17048.45	17230.36	17461.44	17936.26	18529.85	19017.57	19763.49	20509.54	20987.09	22281.40
11	12385.57	12500.65	12836.66	12876.66	13271.87	13720.06	14204.09	14761.63	14904.20	16071.04
12	14613.25	14766.52	15072.32	14674.97	15438.25	15321.41	15266.54	15537.16	15793.72	16555.20
13	13258.91	13423.74	13776.79	13420.85	14089.85	13855.96	14012.14	14292.45	14367.46	15293.38
14	16739.90	16792.58	17039.86	17089.29	17869.24	17647.23	17997.00	18404.94	19071.66	19888.08
15	10930.75	10958.20	11190.46	11745.59	12174.14	12470.40	13160.75	13691.65	14515.68	15547.39
16	17966.12	17865.88	18081.72	18471.11	19035.96	19273.53	19705.18	20117.46	20989.47	21682.21
17	17426.43	17398.06	17686.58	17968.46	18402.84	18656.22	18998.45	19466.44	19700.79	20450.01
18	22093.93	22116.09	22221.25	22371.82	22717.56	22722.28	23107.98	23434.24	23575.59	23948.87
19	18126.89	18196.74	18127.78	18284.93	18416.83	18514.41	18805.41	19261.72	19057.79	19496.46
20	20426.46	20481.57	20356.12	20441.24	20498.63	20458.07	20627.04	20829.74	20905.04	20984.20
21	18910.60	19014.46	18692.78	19008.62	19031.65	19094.89	19006.91	19230.80	19354.39	19612.21
22	22285.06	22321.71	22352.38	22382.13	22567.96	22795.99	22023.00	22234.55	22467.41	22581.94
23	18257.34	18265.85	18361.57	18990.99	18333.22	19574.05	18000.00	18334.52	18479.61	20492.50
24	20712.65	20651.16	20565.61	21139.58	20492.83	21719.59	20333.19	20690.25	20447.89	22334.60
25	15936.07	15886.11	15815.11	16455.85	15766.33	16970.03	16423.68	16304.77	16975.95	19398.11
26	14580.26	14609.98	14619.07	14662.20	15068.86	15315.54	15662.44	16056.44	16914.45	17772.79
27	14342.71	14338.42	14537.03	14549.59	14863.15	15144.25	15261.92	15497.83	16592.20	17357.11
28	11829.07	11910.62	12163.14	12518.73	12852.64	13183.11	13496.92	12623.86	13461.29	14430.30
29	12178.64	12217.65	12338.85	12702.39	12712.52	13109.78	13326.18	12432.83	12519.62	13249.21
30	11796.74	11853.04	11992.38	12319.07	12208.56	12497.04	12861.25	12085.41	12311.72	13204.71
31	15633.80	15583.93	15700.51	15498.49	15585.26	15800.16	15636.99	15754.23	16056.31	16538.70
32	17367.89	17419.71	17665.27	17281.00	17998.34	17765.92	17595.99	17910.79	18227.14	18703.39
33	16728.32	16834.41	17026.17	16552.36	17326.70	17126.21	16898.37	17277.57	17458.67	17870.54
34	15111.38	15237.91	15432.83	15095.66	15660.46	15406.48	15356.11	15820.55	15896.76	16134.13
35	12330.33	12437.01	12597.74	12687.54	12566.13	12974.32	13041.30	13337.38	13451.07	14188.02

Table 20. Manufacturing-In-Process Inventory Level Data

*** RELEASE SIZES ***

WEEK #	0.00	50.00	100.00	150.00	200.00	250.00	300.00	350.00	400.00	500.00
36	11741.62	11824.25	11997.64	12245.49	12014.86	12372.46	12842.73	12822.33	13022.73	13209.98
37	14421.79	14476.25	14667.74	14908.13	14766.31	14968.64	15559.65	15880.47	15669.43	15877.01
38	15853.59	15945.43	15991.22	16259.11	16440.73	15766.59	17210.98	16855.24	16282.63	16265.21
39	13811.52	13784.47	13871.10	14019.00	14342.34	13409.20	14744.89	14657.02	14201.13	14741.93
40	20145.09	20104.45	20101.65	20229.90	20540.51	19608.76	20740.59	20330.32	20400.88	20510.15
41	21416.94	21314.39	21270.89	21354.54	21470.96	21185.25	21327.26	21625.27	21686.05	21567.32
42	32748.07	32704.75	32631.98	32712.32	32855.48	32820.07	32752.85	32383.93	32314.73	31575.59
43	25879.89	25444.42	25793.00	25905.78	26000.46	26022.35	25763.48	25504.21	25566.24	25257.51
44	35343.19	35245.30	35254.31	35382.55	35521.88	35380.76	35401.11	34934.27	35216.81	35190.20
45	27178.97	27119.37	27151.31	27436.88	27637.68	27358.51	27493.67	27616.29	27330.18	27792.45

Table 20 (Continued)

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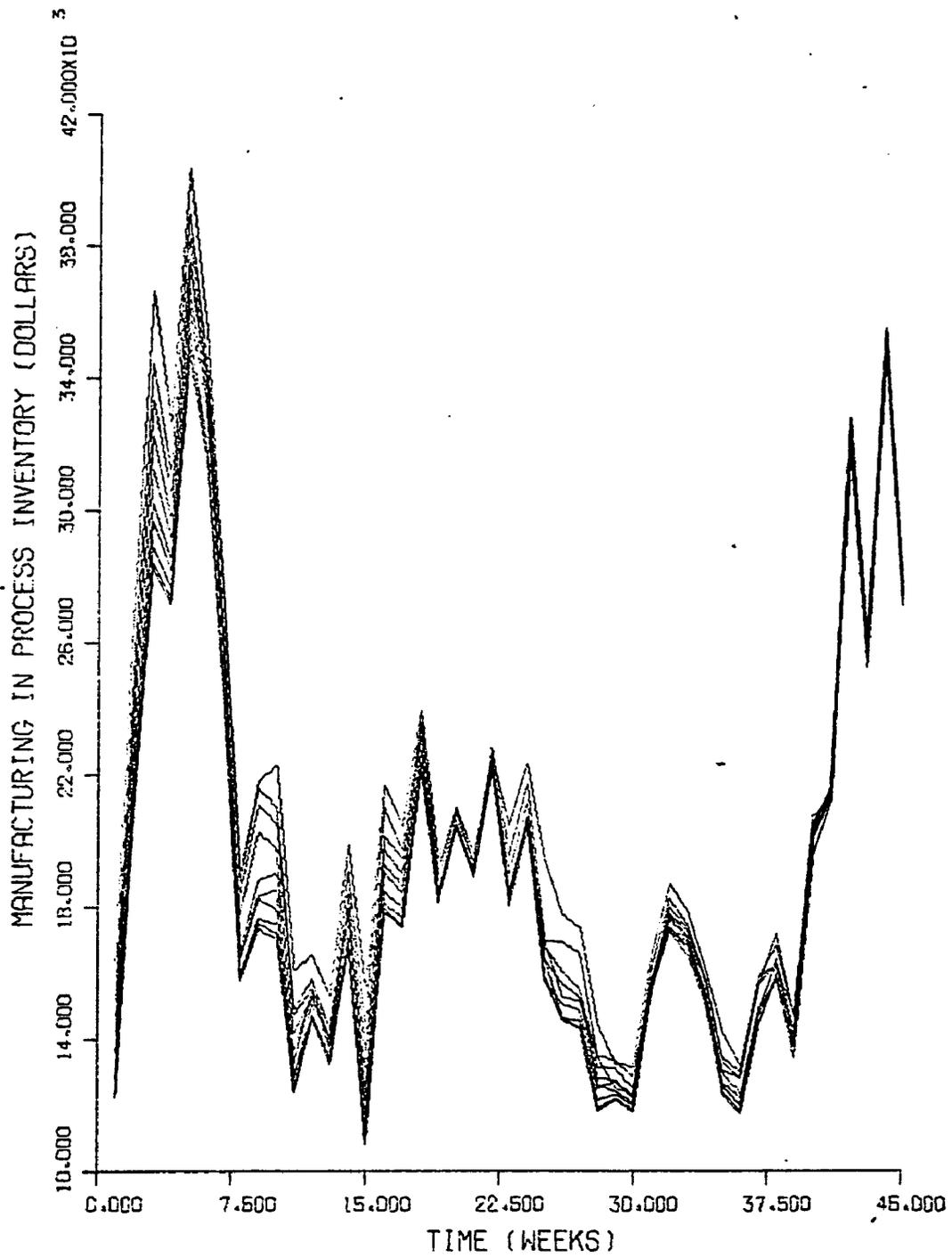
Figure 49. Plot of Manufacturing-In-Process
Inventory Data

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*** RELEASE SIZES ***

WEEK #	50.00	100.00	150.00	200.00	250.00	300.00	350.00	400.00	500.00
1	84.50	272.90	605.78	891.44	1411.01	1933.66	2477.09	3026.91	4145.10
2	143.01	477.34	1079.31	1336.10	2063.70	2794.38	3554.74	4321.47	5931.12
3	183.85	657.31	1447.82	1992.04	3009.79	4047.51	5131.05	6187.10	8378.78
4	150.99	514.26	1035.14	1386.25	2021.19	2651.00	3363.15	4046.79	5487.21
5	180.80	707.22	1421.12	2049.61	2820.58	2830.42	3538.12	4277.42	5649.28
6	190.66	609.36	1166.56	1639.19	2174.07	1879.60	2437.34	2993.97	3957.47
7	167.78	490.26	1271.06	1241.19	1760.55	2173.84	2800.55	3426.71	3183.25
8	164.27	162.10	721.04	670.01	952.66	2001.07	2676.57	3310.41	3058.80
9	181.41	313.90	926.02	995.91	1477.85	2918.09	3778.16	4260.90	4486.60
10	181.91	412.99	887.81	1481.40	1969.12	2715.04	3461.09	3938.64	5232.95
11	114.08	450.09	490.09	885.30	1333.49	1817.52	2375.06	2517.63	3684.47
12	153.27	459.07	61.72	825.00	708.15	653.29	923.91	1180.47	1941.95
13	164.83	517.88	161.94	830.94	597.05	753.23	1033.54	1108.55	2034.97
14	52.68	299.96	348.39	1129.34	907.33	1257.10	1665.04	2331.76	3148.18
15	-72.55	259.71	814.84	1243.39	1539.65	2230.06	2760.90	3584.93	4616.64
16	-100.24	115.60	504.99	1069.84	1307.41	1739.06	2151.34	3023.35	3716.09
17	-28.37	260.15	542.03	976.41	1229.79	1562.02	2040.01	2274.36	3023.58
18	22.16	127.32	277.89	623.63	628.35	1014.05	1340.31	1481.66	1854.94
19	69.65	.89	158.04	289.94	387.52	678.52	1134.83	930.90	1369.57
20	55.11	-70.34	14.78	72.17	31.61	200.58	403.28	478.58	557.74
21	103.86	-17.82	98.02	121.05	184.29	96.31	320.20	443.79	701.61
22	36.65	67.32	97.07	282.90	510.93	-262.06	-46.51	182.35	296.88
23	8.51	104.23	733.65	75.88	1316.71	-257.34	77.18	222.27	2225.16
24	-61.49	-147.04	426.93	-219.82	1006.94	-379.46	-22.40	-764.76	1621.95
25	-47.96	-120.96	519.78	-169.74	1033.96	487.61	868.70	1039.08	3462.04
26	29.72	38.81	81.94	498.60	735.28	1082.18	1476.18	2334.19	3197.53
27	-4.29	194.32	206.88	520.44	801.54	919.21	1155.12	2249.53	3014.40
28	81.55	334.07	689.66	1023.57	1354.04	1667.85	794.79	1632.22	2601.23
29	39.21	160.21	523.75	533.88	931.14	1147.54	254.19	340.98	1070.57
30	56.30	195.64	522.33	411.82	700.30	1064.51	288.67	514.98	1407.97
31	-49.87	66.71	-135.31	-48.54	166.36	3.10	120.43	422.51	904.90
32	51.82	297.38	-86.89	630.45	397.93	228.10	442.90	859.25	1335.50
33	106.09	297.85	-175.96	598.38	397.89	170.05	549.25	730.35	1142.22
34	126.53	321.45	-15.72	549.08	295.10	244.73	709.17	785.38	1022.75
35	106.68	267.41	357.21	235.80	643.92	710.97	1007.05	1120.74	1857.69

Table 21. Manufacturing-In-Process Inventory Level Difference Data

*** RELEASE SIZES ***

# WEEK #	50.00	100.00	150.00	200.00	250.00	300.00	350.00	400.00	500.00
36	82.63	256.02	503.87	273.24	630.84	1101.11	1080.71	1281.11	1468.26
37	54.46	245.95	486.34	344.52	546.85	1137.86	1458.68	1247.64	1455.22
38	91.84	137.63	405.52	597.14	-87.00	1357.39	1001.65	429.04	411.62
39	-27.05	59.58	207.48	530.82	-402.32	933.37	845.50	389.61	930.41
40	-40.64	-43.44	84.81	395.42	-536.33	595.50	185.23	255.79	365.06
41	-102.55	-46.05	-62.40	54.02	-231.69	-89.68	208.33	269.11	150.38
42	-43.32	-116.09	-35.75	107.41	72.00	4.79	-364.14	-433.84	-1172.48
43	-35.47	-86.89	25.89	120.57	142.46	-116.41	-375.68	-313.65	-622.38
44	-97.89	-88.88	39.36	178.69	37.57	57.92	-508.92	-126.38	-167.99
45	-59.60	-27.66	257.91	458.71	179.54	314.70	437.32	151.21	613.48

Table 21 (Continued)

Figure 50. Plot of Manufacturing-In-Process
Inventory Difference Data
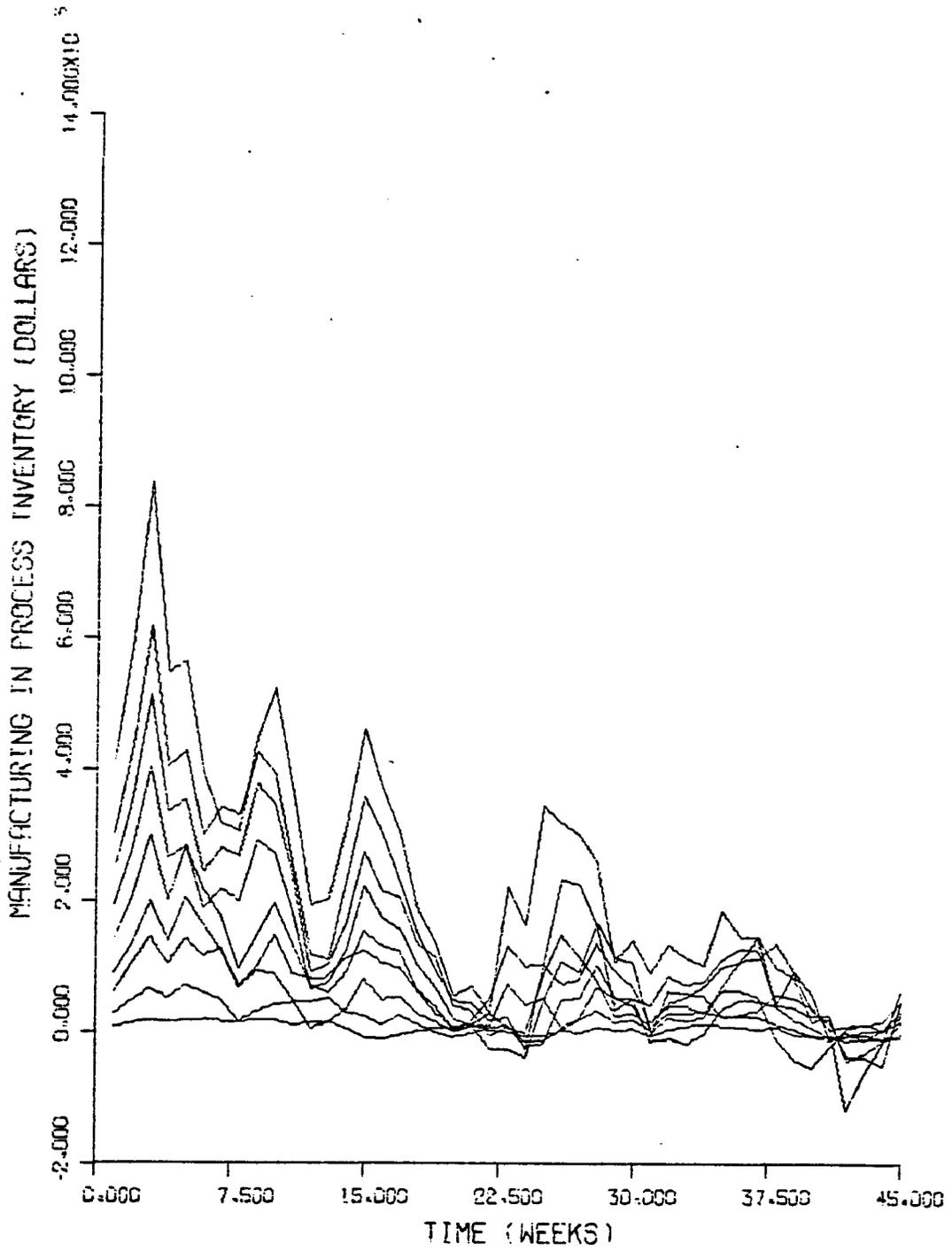
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*** RELEASE SIZES ***

WEEK	0.00	50.00	100.00	150.00	200.00	250.00	300.00	350.00	400.00	500.00
1	89369.00	89617.00	90152.00	91344.00	92144.00	93954.00	95481.00	97139.00	90969.00	102669.00
2	66884.00	66962.00	67190.00	67890.00	68207.00	69040.00	69840.00	70690.00	71540.00	73740.00
3	57680.00	57746.00	58170.00	59007.00	59407.00	60917.00	62136.00	63486.00	64436.00	66556.00
4	87268.00	87598.00	88049.00	88684.00	89334.00	90214.00	90893.00	92006.00	93156.00	95555.00
5	90461.00	90727.00	91253.00	92153.00	92621.00	93271.00	94257.00	94957.00	96057.00	97257.00
6	29662.00	30004.00	30351.00	30901.00	31538.00	32092.00	32136.00	33386.00	34336.00	35864.00
7	29250.00	29396.00	29619.00	30219.00	30119.00	30719.00	30419.00	30924.00	31474.00	37649.00
8	51003.00	51327.00	51873.00	52673.00	53573.00	53984.00	54766.00	55855.00	57055.00	58703.00
9	41700.00	41947.00	42647.00	43077.00	44067.00	45319.00	47099.00	48554.00	49104.00	50862.00
10	30823.00	30979.00	31511.00	32659.00	33336.00	34351.00	35248.00	36198.00	37848.00	39448.00
11	26665.00	26713.00	26615.00	26515.00	26962.00	27412.00	27062.00	27594.00	27062.00	29162.00
12	54942.00	55310.00	55409.00	55409.00	55809.00	57097.00	56195.00	56645.00	57099.00	59072.00
13	16975.00	17049.00	17628.00	18521.00	18367.00	18032.00	20104.00	20642.00	20592.00	22292.00
14	52146.00	52246.00	52286.00	52704.00	53184.00	52688.00	53180.00	53422.00	55220.00	54374.00
15	9570.00	9780.00	10252.00	10324.00	11074.00	11324.00	11224.00	11836.00	12184.00	12684.00
16	72374.00	72460.00	72582.00	72682.00	73282.00	73282.00	74014.00	74050.00	74842.00	75042.00
17	47963.00	48018.00	48177.00	48635.00	48806.00	49270.00	49555.00	50901.00	50317.00	51719.00
18	44663.00	44897.00	45247.00	45606.00	46706.00	46583.00	47991.00	48327.00	49277.00	49809.00
19	42605.00	42702.00	42602.00	42795.00	42362.00	42443.00	43007.00	44085.00	42023.00	43474.00
20	55911.00	55809.00	55775.00	55625.00	55391.00	55325.00	54825.00	54975.00	55925.00	55320.00
21	36844.00	37076.00	37614.00	38232.00	38894.00	39674.00	39450.00	40539.00	41489.00	42551.00
22	70886.00	70884.00	70870.00	70994.00	71129.00	71451.00	71317.00	72261.00	71317.00	70917.00
23	36406.00	36407.00	36658.00	36936.00	36942.00	37892.00	37142.00	37727.00	37868.00	39564.00
24	58263.00	58379.00	58172.00	58480.00	58740.00	58980.00	59486.00	59607.00	60307.00	60583.00
25	22327.00	22378.00	22454.00	22656.00	23006.00	23542.00	23860.00	23760.00	24360.00	25680.00
26	19353.00	19454.00	19886.00	18575.00	19255.00	19559.00	20559.00	20959.00	22959.00	24259.00
27	51960.00	51865.00	52072.00	52232.00	52236.00	52736.00	52868.00	52096.00	52196.00	52596.00
28	11693.00	12021.00	12149.00	14698.00	14612.00	15440.00	16512.00	14499.00	14499.00	16373.00
29	31308.00	31122.00	31217.00	31251.00	31301.00	31451.00	31485.00	31601.00	31985.00	30685.00
30	39149.00	39207.00	39561.00	39303.00	39453.00	39503.00	39760.00	39460.00	40160.00	40505.00
31	44993.00	44907.00	45061.00	44648.00	45448.00	45997.00	45808.00	45157.00	45707.00	46907.00
32	43340.00	43584.00	43992.00	43691.00	44493.00	44741.00	45073.00	45547.00	46397.00	46073.00
33	43438.00	43614.00	43538.00	43562.00	43462.00	43879.00	43430.00	44730.00	44530.00	46230.00
34	31283.00	31353.00	31603.00	31729.00	31779.00	32279.00	32379.00	32629.00	32479.00	33479.00
35	18603.00	18681.00	18647.00	19021.00	17647.00	18819.00	18456.00	17940.00	18708.00	19308.00

Table 22. Number of Pieces Scheduled Data

*** RELEASE SIZES ***

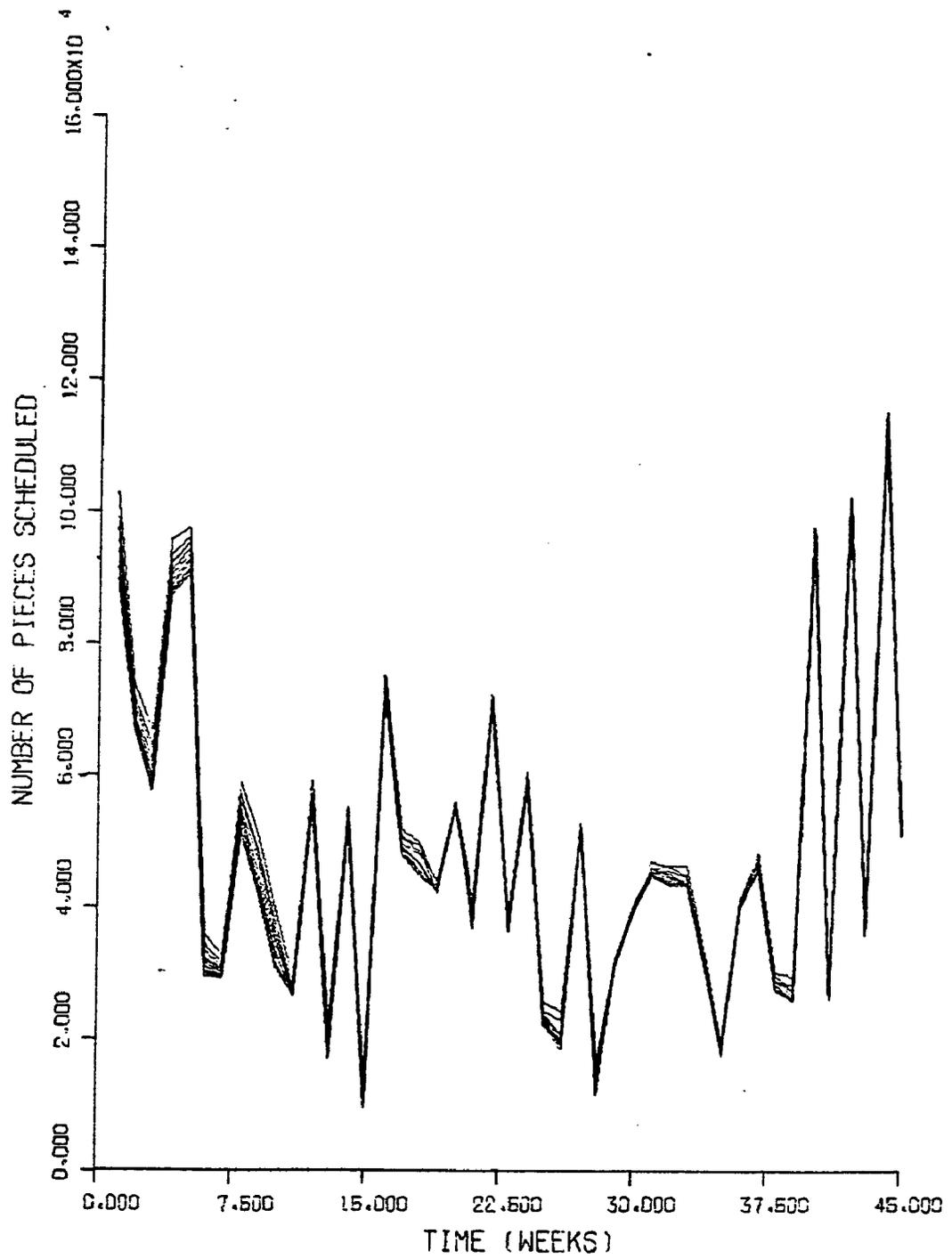| * WEEK *	0.00	50.00	100.00	150.00	200.00	250.00	300.00	350.00	400.00	500.00
36	40228.00	40362.00	40526.00	40606.00	39906.00	39940.00	41220.00	41170.00	40920.00	41281.00
37	45707.00	45553.00	45869.00	46069.00	45469.00	45944.00	46962.00	49296.00	46536.00	47336.00
38	27454.00	27922.00	27832.00	28284.00	28914.00	28352.00	28950.00	29302.00	29802.00	30202.00
39	25970.00	25906.00	26108.00	26112.00	26660.00	25970.00	27374.00	27344.00	28274.00	29574.30
40	97882.00	97710.00	97406.00	97364.00	97810.00	96954.00	96666.00	96534.00	97434.00	95234.00
41	26710.00	26758.00	26890.00	26568.00	25774.00	26556.00	26690.00	26012.00	27012.00	27196.00
42	102113.00	101301.00	101637.00	101809.00	101757.00	102251.00	102313.00	101255.00	100903.00	99837.00
43	36919.00	36735.00	36701.00	36769.00	37153.00	36842.00	35842.00	37306.00	38194.00	37794.00
44	111913.00	111861.00	112345.00	112933.00	113603.00	113041.00	113889.00	112936.00	113897.00	115434.00
45	51110.00	51132.00	50953.00	51429.00	51729.00	51509.00	52085.00	52725.00	51375.00	50527.00

Table 22 (Continued)

Figure 51. Plot of Number of Pieces Scheduled Data

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*** RELEASE SIZES ***

WEEK	50.00	100.00	150.00	200.00	250.00	300.00	350.00	400.00	500.00
1	248.00	783.00	1975.00	2775.00	4589.00	6112.00	7830.00	9600.00	13300.00
2	78.00	306.00	1006.00	1356.0C	2156.00	2956.00	3806.00	4656.00	6856.00
3	106.00	490.00	1327.00	2127.00	3237.00	4456.00	5806.00	5756.00	8876.00
4	330.00	780.00	1416.00	2066.00	2946.00	3625.00	4738.00	5888.00	8288.00
5	266.00	792.00	1692.00	2160.00	2810.00	3796.00	4496.00	5596.00	6796.00
6	342.00	689.00	1239.00	1976.00	2430.00	2474.00	3724.00	4674.00	6202.00
7	136.00	369.00	969.00	869.00	1469.00	1169.00	1674.00	2224.00	3399.00
8	324.00	870.00	1670.00	2570.00	2981.00	3763.00	4852.00	6052.00	7700.00
9	247.00	947.00	1377.00	2367.00	3619.00	5399.00	6854.00	6404.00	9162.00
10	156.00	688.00	1836.00	2513.00	3528.00	4425.00	5375.00	7025.00	8625.00
11	48.00	-50.00	-150.00	297.00	747.00	397.00	929.00	397.00	2497.00
12	368.00	467.00	467.00	857.00	2155.00	1253.00	1703.00	2157.00	4130.00
13	114.00	653.00	1546.00	1392.00	1057.00	3129.00	3667.00	3617.00	5317.00
14	100.00	140.00	558.00	1038.0C	742.00	1034.00	1276.00	3074.00	2178.00
15	210.00	682.00	754.00	1504.0C	1754.00	1654.00	2264.00	2614.00	3114.00
16	86.00	208.00	308.00	908.00	908.00	1640.00	1676.00	2468.00	2668.00
17	55.00	214.00	672.00	843.00	1307.00	1592.00	2838.00	2354.00	3756.00
18	234.00	584.00	943.00	2043.00	1920.00	3328.00	3664.00	4614.00	5146.00
19	17.00	-83.00	111.00	-323.0C	-242.00	322.00	1400.00	-662.00	789.00
20	-102.00	-136.00	-286.00	-520.00	-586.00	-1086.00	-936.00	14.00	-591.00
21	232.00	770.00	1388.00	2050.00	2830.00	3006.00	3695.00	4645.00	5707.00
22	-2.00	-16.00	112.00	243.00	565.00	431.00	1375.00	431.00	31.00
23	1.00	252.00	530.00	536.00	1486.00	736.00	1321.00	1462.00	3158.00
24	116.00	-91.00	217.00	517.00	717.00	1223.00	1344.00	2044.00	2320.00
25	51.00	127.00	329.00	679.00	1215.00	1533.00	1433.00	2033.00	3353.00
26	101.00	533.00	-778.00	-98.00	206.00	1206.00	1606.00	7506.00	4906.00
27	-95.00	112.00	272.00	276.00	776.00	908.00	136.00	236.00	636.00
28	328.00	456.00	3005.00	2919.00	3747.00	4819.00	2806.00	2806.00	4630.00
29	-186.00	-91.00	-57.00	-7.00	143.00	177.00	293.00	677.00	-623.00
30	58.00	412.00	154.00	304.00	354.00	611.00	311.00	1011.00	1356.00
31	-86.00	68.00	-345.00	455.00	1004.00	815.00	164.00	714.00	1914.00
32	244.00	652.00	351.00	1153.00	1441.00	1733.00	2207.00	3057.00	2733.00
33	176.00	100.00	124.00	24.00	441.00	-8.00	1292.00	1092.00	2792.00
34	70.00	320.00	446.00	496.00	996.00	1096.00	1346.00	1196.00	2196.00
35	72.00	38.00	412.00	-962.00	210.00	-153.00	-669.00	99.00	699.00

Table 23. Number of Pieces Scheduled Difference Data

*** RELEASE SIZES ***

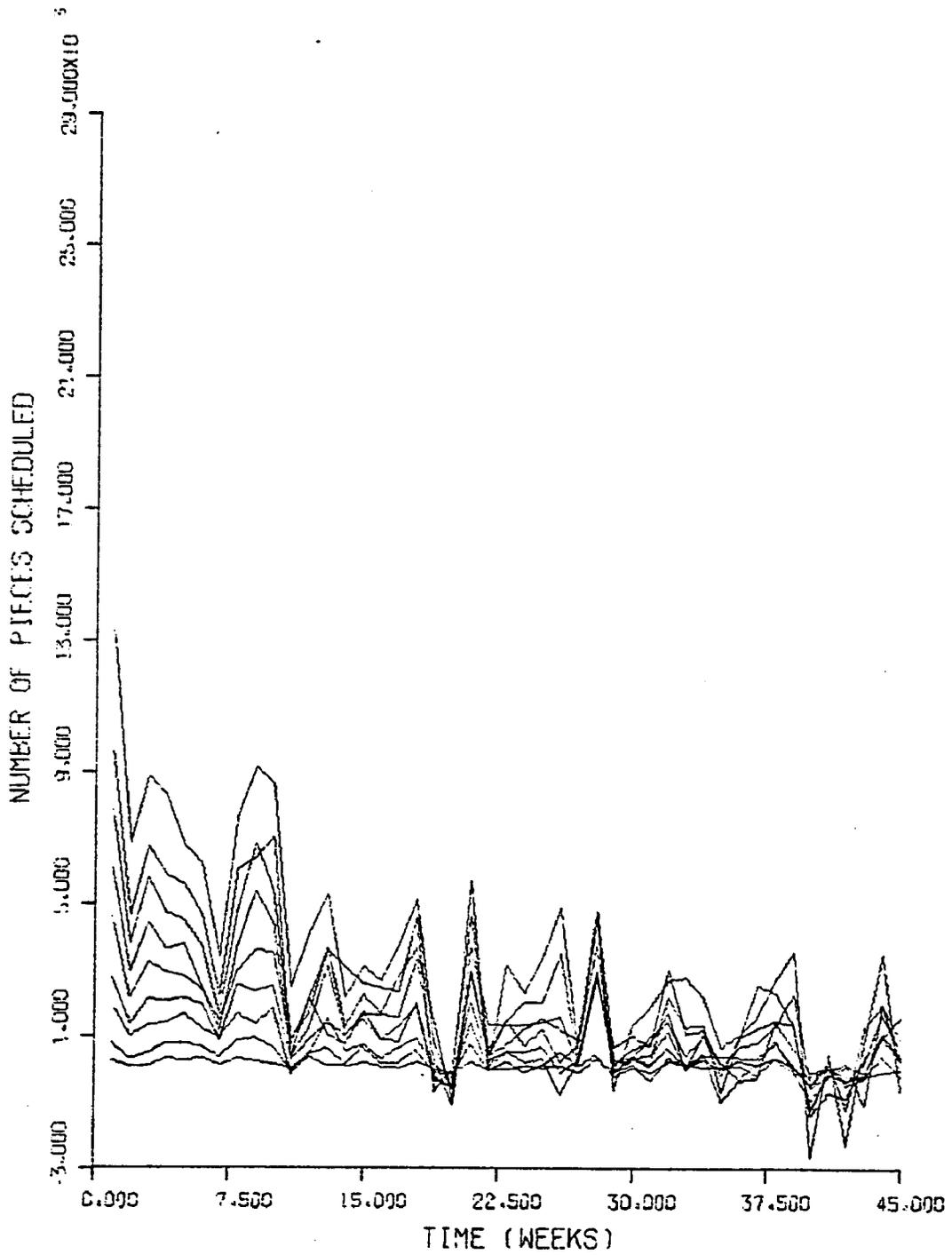| * WEEK *	50.00	100.00	150.00	200.00	250.00	300.00	350.00	400.00	500.00
36	134.00	298.00	378.00	-322.00	-288.00	992.00	942.00	692.00	1053.00
37	-154.00	162.00	362.00	-238.00	237.00	1255.00	2579.00	829.00	1629.00
38	368.00	378.00	830.00	1460.00	898.00	1496.00	2348.00	1348.00	2748.00
39	-64.00	138.00	142.00	690.00	0.00	1404.00	1374.00	2304.00	3604.00
40	-172.00	-476.00	-518.00	-72.00	-928.00	-1216.00	-1348.00	-448.00	-2648.00
41	48.00	180.00	-142.00	64.00	-154.00	-20.00	-638.00	302.00	486.00
42	-212.00	-476.00	-304.00	-356.00	138.00	200.00	-858.00	-1210.00	-2276.00
43	-184.00	-218.00	-150.00	234.00	-77.00	-1077.00	387.00	1275.00	875.00
44	-52.00	432.00	1020.00	1690.00	1128.00	1976.00	1023.00	1984.00	3521.00
45	22.00	-157.00	319.00	619.00	399.00	975.00	1615.00	765.00	-583.00

Table 23 (Continued)

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Figure 52. Plot of Number of Pieces Scheduled
Difference Data

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*** RELEASE SIZES ***

WEEK	0.00	50.00	100.00	150.00	200.00	250.00	300.00	350.00	400.00	500.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	20045.88	20066.21	20067.36	20116.18	20140.94	20185.24	20210.01	20210.01	20226.30	20226.30
5	15436.22	15431.46	15441.01	15443.25	15425.96	15425.97	15425.98	15448.21	15470.45	15535.56
6	11812.57	11808.10	11810.75	11778.14	11764.24	11764.38	11800.85	11800.87	11752.20	11747.87
7	20311.10	20315.95	20326.13	20324.43	20318.33	20392.36	20338.25	20338.25	20338.26	20338.29
8	27878.93	27879.49	27871.33	27882.27	28156.98	28087.73	27936.01	27904.51	27924.41	27961.92
9	5968.80	6013.74	6107.08	6223.65	6263.97	6314.06	6314.68	6467.91	6629.00	6798.26
10	5254.49	5260.72	5281.70	5262.40	5035.30	5020.13	5155.87	5083.52	4996.66	5083.44
11	12447.56	12463.97	12449.33	12497.11	12439.43	12393.84	12418.16	12412.08	12497.13	12274.36
12	8825.48	8750.15	8705.17	8582.13	8618.05	8566.05	8514.02	8517.48	8317.91	8240.61
13	4099.36	4080.41	4067.06	4101.40	4091.58	4083.66	4086.39	4022.85	4048.46	4043.66
14	3162.58	3193.43	3145.50	3037.71	3065.17	3090.90	3064.47	3075.46	2946.86	3022.87
15	10206.44	10215.88	10221.79	10168.25	10251.41	10269.82	10212.86	10187.82	10379.91	10291.68
16	5277.64	5280.73	5270.28	5272.03	5217.43	5231.36	5287.85	5331.98	5150.73	5344.33
17	13763.07	13735.91	13709.29	13663.95	13654.14	13611.64	13612.97	13583.49	13841.49	13618.79
18	2841.55	2807.66	2800.27	2760.27	2648.84	2661.77	2585.28	2565.94	2540.56	2416.08
19	14684.47	14710.91	14728.80	14674.91	14713.73	14715.24	14527.01	14493.87	14644.37	14667.18
20	14185.18	14186.27	14177.71	14147.25	14133.14	13992.72	14072.26	13912.41	13716.44	13693.56
21	10942.55	10957.91	10949.58	10889.72	10926.37	10868.86	10856.35	10745.06	10695.44	10662.09
22	9669.55	9628.58	9595.30	9824.80	9971.16	10045.73	10520.71	10519.55	10329.84	10226.29
23	15400.32	15369.99	15411.88	15388.46	15358.26	15382.32	15425.46	15427.46	15409.43	15443.81
24	9818.64	9840.19	9828.08	9839.12	9751.50	9815.27	9523.55	9314.80	9355.76	8471.03
25	14349.29	14385.74	14400.57	14138.37	13877.97	13626.62	13292.59	13229.49	13150.34	13080.07
26	6735.32	6677.32	6624.07	6622.98	6445.84	6528.93	6343.51	6259.51	6136.14	6299.64
27	12705.64	12719.95	12707.01	12736.01	12766.96	12807.27	12833.75	12863.14	12836.53	12733.97
28	4966.04	4963.95	4957.80	4918.43	4967.93	4923.65	4944.16	4937.25	4917.84	4915.24
29	4064.48	4044.36	4019.43	4037.08	4063.17	4102.51	4032.28	4124.14	4062.94	4130.10
30	11165.43	11150.70	11128.88	11072.05	11002.98	10939.48	10897.80	10811.55	10840.22	10838.06
31	2605.27	2604.06	2579.35	2608.30	2579.58	2628.86	2625.60	2651.71	2533.37	2607.50
32	4360.36	4341.42	4359.51	4367.11	4327.46	4257.25	4301.50	4121.97	4299.71	4027.14
33	13224.71	13095.54	13086.05	13117.50	13201.19	13180.84	13198.18	13240.32	13281.71	13311.55
34	8625.12	8617.64	8633.21	8534.68	8660.14	8662.53	8449.61	8346.84	8386.13	8409.39
35	8780.51	8794.08	8756.13	8757.25	8776.52	8711.72	8711.30	8724.97	8675.10	8768.14

Table 24. Assembly-In-Process Inventory Data

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| WEEK	0.00	50.00	100.00	150.00	200.00	250.00	300.00	350.00	400.00	500.00
36	8376.4C	8373.29	8350.45	8254.37	8255.45	8267.04	8160.46	8201.63	8274.62	7996.39
37	6778.17	6776.84	6764.67	6750.84	6721.78	6654.3E	6710.34	E821.65	6779.04	6844.51
38	3056.29	7069.29	3131.77	3193.00	3062.07	3270.59	30E8.23	7183.34	3325.80	3221.20
39	10410.03	10410.24	10442.56	10443.27	10507.28	10489.82	10545.21	10518.92	10400.78	10457.61
40	10168.21	10151.07	10175.01	10198.70	10075.2E	10183.04	10186.50	1C302.86	10106.36	10390.60
41	6266.74	6237.60	6175.74	6093.48	6184.80	5963.10	6096.58	5992.40	5964.21	5715.02
42	7002.01	6955.80	6788.70	6641.23	6605.97	5834.59	5846.15	E081.00	5949.54	5551.R0
43	19395.60	19175.70	19315.57	19194.14	19258.65	19223.71	19028.36	18933.42	18997.21	18711.03
44	7882.07	7870.57	7872.83	7787.45	7775.63	7717.61	7788.61	7624.34	7278.52	7266.06
45	25223.79	25215.53	25189.25	25171.61	25146.00	25156.43	25175.36	25111.69	25130.99	25100.57

Table 24 (Continued)

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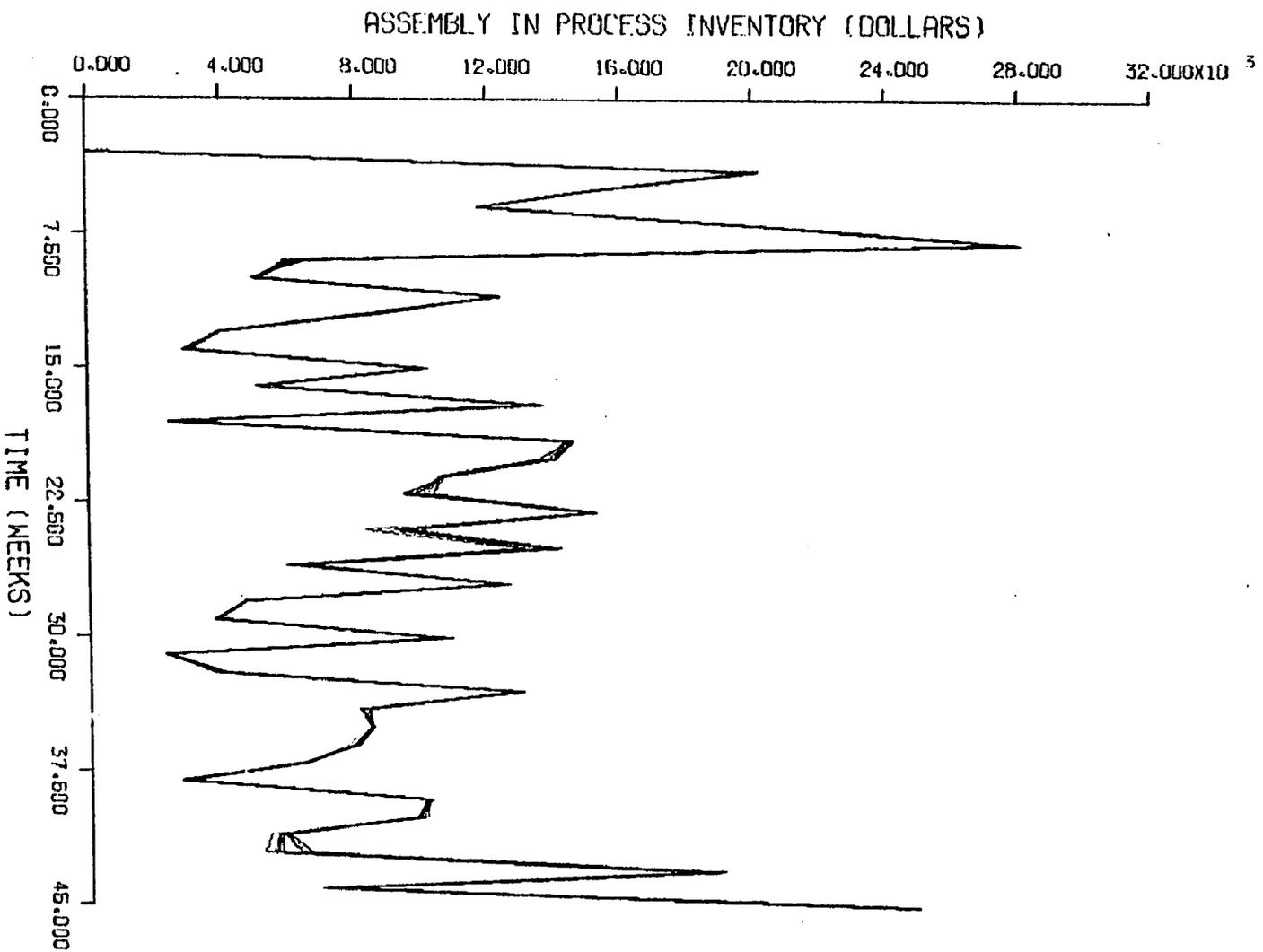
Figure 53. Plot of Assembly-In-Process Data

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4.4 Customer Service Data

The satisfaction of the customer by supplying quality product without excessive delay is one of the prime considerations when determining and/or evaluating an inventory policy. The customer service level for the inventoried items and the non-inventoried items was determined from the simulation and/or via random sampling.

During the simulation of the order entry/production-inventory system, order service information under the current policy was obtained. Of the three thousand three hundred and eighty-six (3386) orders that were processed during the simulation, two thousand and fifty-five (2055) or sixty and six tenths (60.6) percent were for items which are normally inventoried; of these orders, ninety and three tenths (90.3) percent were filled upon receipt, seven and four tenths (7.4) percent were partially filled and two and two tenths (2.2) percent were backordered. All of the orders (1331) for non-inventoried items were backordered.

The long term service levels for the inventoried items under the various levels will not differ from the current levels as the manufacturing orders for these items exceed the minimum lot sizes under test and no component inventory will be built for these items. The long term customer service, as measured by the number of orders for

currently non-inventoried items that are assembled upon receipt (thereby greatly reducing the time necessary to complete the order) was estimated via random sampling. The procedure used for this sampling was to randomly access a product in the order file and randomly determine the initial component inventory that would be available for use in filling the orders under the long term conditions and estimating the number of orders for the product that will be filled upon receipt. A sample of one hundred and seventy-five (175) orders was taken and used to estimate the customer service under the various levels of the decision rule. The estimates are shown in Table 25.

The time between implementation of the decision rule and the realization of the long term customer service levels was estimated via the simulation and discussions with operating personnel. This time delay is due to the shop practice of not manufacturing an item until an order is received for it. This practice will thus build up the component inventory over time and customer service will increase as the component inventory is built.

Customer service data was gathered via the simulation model and is shown in Table 26.

Using the data in Table 26 and discussions with

operating personnel, a time delay of three (3) to four (4) years between implementation and achievement of customer service levels was made.

Minimum Release Size	Percentage of Orders for Non-inventoried Items Assembled Upon Receipt	Total Customer Service- Percentage of Orders Filled, Partially Filled, and Assembled Upon Receipt
0	-	59.3
50	25	69.2
100	38	74.3
150	42	75.8
200	57	81.7
250	61	83.3
300	62	83.7
350	68	86.0
400	71	87.2
500	72	87.6

Table 25. Estimated Customer Service for the Levels of Decision Rule

Minimum Manufacturing Lot Size	Customer Service Over 1st 20 Simulated Weeks	Customer Service Over Final 25 Weeks of the 45 Week Simulation	Estimated Long Term Customer Service
50	5.7	11.0	25
100	8.2	17.3	38
150	10.1	24.1	42
200	13.2	28.4	57
250	15.7	34.4	61
300	19.7	38.9	62
350	21.0	42.1	68
400	24.1	42.1	71
500	26.3	52.7	72

Table 26. Customer Service Data

4.5 Validation

Validation of this simulation was made through extensive program testing and discussions with operating personnel. The simulation model was tested extensively for both subprogram execution and subprogram interaction validity. All trends shown in the time series data generated during the simulation experiments were discussed with operating personnel to determine the "reasonableness" of the data.

The lack of data hindered validation to some extent. Only one year of order history data was available and thus simulation experiments which used historical orders as its powering mechanism could not be run for more than one year. Longer runs using data drawn from statistical distributions of orders were infeasible in that the products under study were ordered infrequently and distributions could not be hypothesized with a reasonably high degree of confidence and the number of distributions to be hypothesized was extremely large.

4.6   Determination of the Best Policy

The optimum minimum lot size policy is the policy which balances the increased in inventory carrying costs and the increase in benefits which accrue due to the reduction in setups and increased customer service. These costs and benefits are summarized in Table 27; from this table management was able to determine the best policy. The range of i values was included to demonstrate the sensitivity of the decision to the value of i which includes interest, carrying and obsolescence costs and may vary over time.

Minimum Release Size	Set-up Charges				Inventory Changes				Cust. Service
	Reduction in No. of Setups	Reduction in Set-up Hours	Cost Reduction @ Regular Time Rates	Cost Reduction @ Over-time Rate	Investment Changes	Carrying Charges i=20	i=25	i=30	
0	-	-	-	-	-	-	-	-	59.3
50	192	176	1032	1548	1601	320	400	480	69.2
100	314	288	1690	2535	5744	1149	1436	1723	74.3
150	452	415	2435	3653	11798	2360	2949	3539	75.8
200	546	501	2940	4410	17722	3544	4430	5316	81.7
250	610	560	3286	4939	25355	5071	6335	7606	83.3
300	674	618	3626	5439	30393	6079	7598	9117	83.7
350	742	681	4354	6531	38604	7721	9657	11581	86.0
400	789	724	4248	6372	47700	9540	11925	14310	87.2
500	860	789	4630	6945	67248	13449	16812	20174	87.6

Table 27. Summary of Costs and Benefits

CHAPTER 5   CONCLUSIONS AND AREAS FOR FURTHER STUDY

5.1   Conclusions

The conclusions that can be drawn from this study relate to the use of simulation as the methodology for investigation of the effect of a minimum manufacturing lot size decision rule and to the economic advantages of the use of the decision rule on products in the declining stages of the product life cycle.

Simulation of the order entry/production inventory system provided an appropriate investigation and evaluation methodology. The appropriateness of this solution is due to its allowance for the incorporation of complex interactions among products and customer orders over time and its ability to provide insight into both the long term and transient effects attributable to the implementation of the decision rule. While not all interactions were modelled, all of the major interactions could be incorporated in the model and the accuracy obtained did not suffer from the lack of a large amount of data that most analytical models would require. Simulation, however, is not without its pitfalls. It was costly to develop, validate, and run the simulation model and the transferability of the numerical results on other than a general basis is questionable.

The use of the decision rule proposed in industries

which manufacture replacement and/or repair parts for long-lived products (e.g. cars, trucks, tractors, consumer durables) has considerable economic benefit as the products approach the end of their lives. These economic benefits are realized though from a reduction in set-up costs and an increase in customer service which outweighs the additional inventory carrying cost. The use of this type of decision rule will increase the productive capacity of the manufacturing facility and may enable earlier retirement of production equipment and a resultant freeing of capital and production floor space. The use of the decision rule will also aid in production scheduling by reducing the number of different products that are in production on a per unit time basis.

5.2 Areas for Further Study

Further study in the determination of inventory policies for products in the declining phase of the product life cycle should be directed to three areas:

1. Identification of the start of a product's entry into the decline phase of its life.

2. Investigation into the effect of the division of the decline phase of the product life into classes with each class having a different inventory policy.

3. Development of an analytical model or methodology for products in this phase of their life.

The identification of the time that a product enters the decline phase of its life is, of course, central to the effective implementation of an inventory policy for products in decline. The means of identification should be simple, accurate and easily incorporated into existing inventory control systems.

Once identified, an economic improvement may result from the division of the products in decline into classes which have different inventory policies (e.g. class 1 lot size = 500 pieces, class 2 lot size = 350 pieces, etc.). Research should be conducted to determine if the setting up of classes for the products will be economically beneficial, how many classes should be set up

and what characteristic(s) should be used to differentiate the products into the classes-demand, frequency of order, set-up cost, etc.

The determination of an analytical solution for problems of this type which is applicable to individual items and yields optimum or near optimum results under real world conditions, if possible, would be the most fruitful area for further research. This model should be low in cost (in terms of dollar and data costs) and easily applied, and understood.

APPENDIX I   BACKGROUND OF INVENTORY CONTROL
COSTS AND MODELS

A.1   Overview

The following section is intended to give back-
ground in the various trade-offs that must be considered
in inventory control and in the development, and limi-
tations of the various inventory models. The discussion
of the applicability of these models to the specific
situation was discussed in chapter two.

A.2 Background

There are three sets of cost which must be considered when one is trying to control his/her inventory in an optimum fashion. One set of costs increases as batch size increases while another decreases as batch size decreases. The set-up costs which are directly related to batch size and the inventory carrying cost which are inversely related to batch size must be considered in every inventory model. As model builders have attempted to more closely model the real world situations, customer service costs have been included in the decision parameters, and, in multi-period seasonal or varying demand models the cost of changing the size of the workforce is included.

Set-up costs, as the name implies, are the costs associated with the readying of a machine (or series of machines) for the manufacture of a product, i.e. all required tooling, jigs, fixtures, controls, etc. must be mounted on the equipment and all clearances must be set and several parts must be run on the equipment to ascertain the conformity of the parts produced with the part's specifications, making any adjustments to the equipment to assure the quality of the parts produced. This set of costs will be incurred each time the equipment must be set up for the part's manufacture. The

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cost of setting up the equipment is usually apportioned to each piece manufactured using the particular setup by division of the total set-up cost by the number of pieces that were produced by the setup. The set-up cost, as measured on a per piece basis, will decrease as the divisor (number of pieces in the lot) increases; the set-up cost, as measured on a unit time basis, would show the same decrease as the number of setups per unit time for a given demand pattern will decrease.

Inventory carrying cost is the set of costs associated with the maintenance of a stock of product to meet anticipated demand. In batch, or intermittent manufacturing, inventory is used to supply the demand which occurs during the interval of time between production runs. Components of the inventory carrying cost are: the rental or, in the case of an owned warehousing system, the depreciation cost associated with the maintenance of warehousing space for the product; the interest cost associated with the value (in terms of dollars) held in inventory that could be earning interest if it were not tied up in inventory; the cost of obsolescence, or the cost associated with the scrapping or the sale at reduced prices (often below cost) of the inventory of product for which the anticipated demand is not met due to the discovery of a cheaper and/

or more efficient substitute, government edict, etc.;
the cost of maintaining security for the inventory, or
the cost of pilferage and/or its prevention (watchpersons
and other anti-theft devices) and insurance and fire
protection systems; the cost of taxes on inventory; and
any special considerations that must be made for the
inventory, refrigeration, heating, shielding (radio-
activity), etc. This set of costs will be incurred
continuously during the time that inventory is maintained;
and, since these costs rise directly with the size of
the inventory, will rise as the amount of inventory
maintained is increased. The amount of inventory that
must be maintained increases as the manufacturing lot
size increases, as the maximum amount of stock is
closely related to the lot size, and as this amount of
stock is increased it must be maintained for a relatively
longer period of time (assuming a stable demand rate).

The cost of maintaining customer service, which is
included as the models become more "realistic" is the
cost of maintaining sufficient inventory to cover
fluctuations in demand so that customer's demands can be
filled within a reasonably short period of time after
request, and may be of primary importance in a highly
service competitive market situation and is another cost
that must frequently be considered during the formula-

tion of an inventory policy. Customer service is maintained by keeping an amount of goods in stock that is higher than would be required under "normal" demand conditions, so that if customers' demands are higher than anticipated between production runs, sufficient stock will be available to fill their demand. This extra stock is called a safety stock, and is necessitated by the inability of manufacturing systems to react instantaneously to demand fluctuations and variable lead times (times associated with the manufacturing operations, the sum of the operation times being the shortest time in which the product can be supplied to the customer, and times associated with the time between the placement of an order for materials, etc. and their receipt). A relatively larger safety stock will reduce the costs associated with stocking out, that is, the cost stemming from the inability to satisfy a customer's demand quickly enough to avoid incurring a loss of business (cancellation of the order because of an excessive waiting time) and/or a loss of goodwill (customer dissatisfaction which causes the customer to direct future orders to other suppliers); but will increase inventory carrying costs due to the larger stock that must be carried.

The cost of hiring and firing workers is the cost of adjusting the production rate upward or downward as demand for product increases or decreases. The hiring of workers incurs costs related to advertising, interviewing, records gathering and initiation, and training. These costs generally increase as the number of workers hired per period increases; the rate of increase in cost is dependent upon the labor force in the geographical region and as more workers are hired, less and less qualified individuals are hired increasing selection and training costs. The firing of workers also incurs costs in the form of higher unemployment tapes, reduced community relations, reduced worker morale, and losses in productivity prior to a layoff as workers attempt to make or prolong the work that is available.

The models that have been developed have attempted to balance these costs under various assumptions. The progress in inventory models has been marked by the reduction in the number of assumptions that are used in the various models.

A.3 Inventory Models

The models used in the analysis of inventory analysis have become increasingly complex as their authors have attempted to reduce the number of assumptions that had to be incorporated into the model. The number of assumptions, in general, reduces the degree to which the model reflects the real system. These departures from reality are made in an effort to reduce the amount of computation involved or to facilitate understanding of the basic cost trade-offs that must be made in order to determine the correct inventory decision.

The number of trade-offs and real-world complexities that must be incorporated in a model depends upon the particular system being studied and the accuracy with which the model is to reflect the particular system. As models increase in complexity and more closely reflect reality they consider more of the possible costs, variations, and interactions that occur in the real system. The following sections are intended to give background in the major categories of inventory models which constitute the theoretical background for this study.

Single Product - Deterministic Model

The classic manufacturing lot size model is a single product constant demand model which was developed as an aid in the determination of the "best" lot size to use

in manufacturing. It makes several simplifying assumptions in order to gain ease of understanding and computat on and is known as the Wilson or Square Root Model. This model attempts to determine the "best" lot sizing decision by balancing the set-up and inventory carrying costs associated with the manufacturing of a particular product in batches. The model is robust but performs best in situations where no multi-product interactions (competition among products for production time on the same machine or line) occur and demand occurs in a deterministic fashion, i.e. a constant rate.

The Wilson model also assumes a constant and known production rate, for the product (an infinite production rate is the case of the wholesaler-retailer who receive the entire lot at one instant rather than over time and constant and known lead and set-up times. The model is shown diagrammatically in Figure 54. In Figure 54, the lot size is shown; this quantity of goods is produced at a constant rate (M), and placed into inventory at a rate (M - D), that is, the manufacturing rate (M) less the demand rate (D), during the time of manufacture (T_1). At the end of the manufacturing portion of the cycle, there is a period of time during which the inventory that was build during the time of manufacture is used to fill orders, and the equipment is used to manufacture other products; this period of time, the use only portion
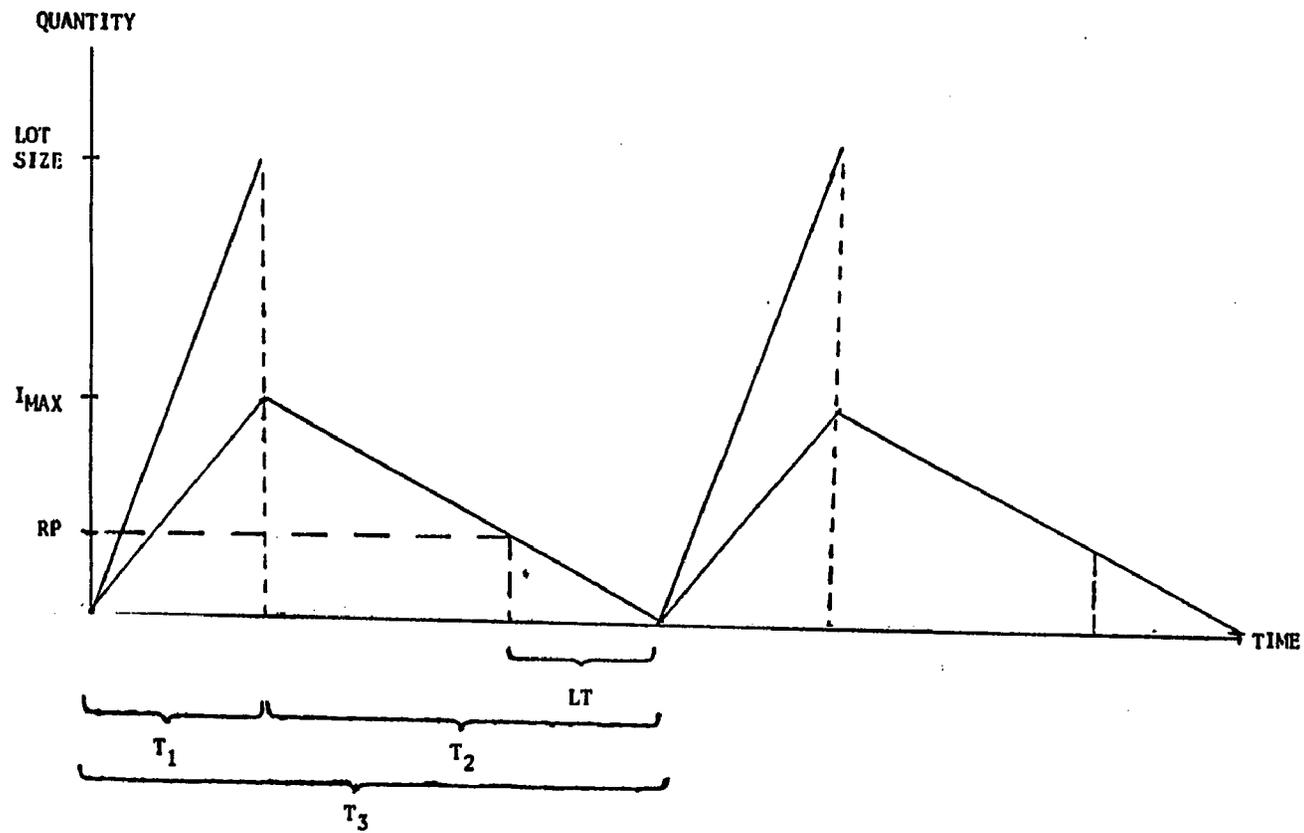
Figure 54. Classic Single Product Manufacturing Lot Size Model

of the cycle, is shown as T_2 in Figure 54. During the
period of use only, the inventory steadily declines
until the reorder point (RP) is reached; the reorder
point is the quantity of inventory that would normally
be required to meet demand during the time required to
set up and secure the equipment and materials required
for the production of this product. A complete cycle
takes a period of time shown as T_3 in Figure 54. As can
be seen from the figure, the inventory level when manu-
facturing begins is zero. The implication of this under
conditions of varying demand will be discussed later.

The manufacturing lot size which minimizes the cost
of setup and inventory carrying is determined using
calculus to find the minimum of the total cost curve for
this model. The total cost curve is defined by the
following equation:

$$TC = (D/Q)*(SU) + Q*(1-D/M)*(CC) \qquad (7)$$

where

      TC = Total cost per unit time

      D = Demand rate (per unit time)

      SU = Set-up cost (per run)

      Q = Quantity in the manufacturing lot

      M = Manufacturing rate (per unit time)

      CC = Carrying Cost (per unit of inventory
           per unit time - based on the maximum
           amount of inventory)

Differentiating and solving for the optimum batch size Q*, the result is

$$Q^* = \sqrt{D^*(SU)/((1-D/M)(CC))} \qquad (8)$$

The reorder point can be calculated as

$$RP = (LT)(D) \qquad (9)$$

where

RP = Reorder Point

LT = Lead Time

D = Demand rate (per unit time)

To illustrate the use of the Wilson Model the following example is considered:

D = 100,000 units/year

SU = 10 dollars/setup

M = 500,000 units/year

CC = 3 dollars/unit/year

LT = 2 days

Using the Wilson Model, the optimum batch size, Q*, is calculated:

$$Q^* = \sqrt{100,000^*10/((1-.2)^*3)}$$
$$= \sqrt{416,666.67}$$
$$= 645.5 \text{ or } 646$$

The order quantity may be rounded off in cases where the product is indivisible (e.g. an order for one half of a tire would not make any sense) with a negligible increase in cost over the "best" but impractical policy.

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The total cost and cycle times may now be calculated:

$$TC = (D/Q*)(SU) + (1-D/M)(Q*)(CC)$$
$$= (100,000/646)(10) + (646)(1-.2)(3)$$
$$= 1547.99 + 1550.40$$
$$= 3098.39 \text{ dollars}$$

and

$$T_1 = Q*/M = 646/2000 = .323 \text{ days}$$

$$T_2 = Q*(1-D/M)/D = 517/400 = 1.293$$

$$T_3 = Q*/D = 646/400 = 1.615$$

The sensitivity of total cost to the batch size is relatively low. As shown in Table 28 below, the batch size can vary to a large degree from the "best" size without a large increase in costs.

Single Product - Stochastic Models

Two of the major drawbacks of the Wilson Model are its assumption of a constant, known demand which occurs uniformily over time and its assumption of a constant and known lead time. In many inventory situations, one or both of the above assumptions may not be valid; in these cases, a model which may improve inventory control would incorporate consideration of the variability of demand, lead time or both into its mathematical formulation. By use of statistical distributions to describe the demand and/or lead time variability, this type of

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Q	Number of Setups Per Year	Set-up Cost Per Year	Maximum Inventory (½Q)	Inventory Carrying Cost/Year	Total Cost Per Year
1	100,000	1,000,000	0	0	1,000,000
300	333.3	3,333	240	720	4,053
600	166.7	1,667	480	1,440	3,107
646	154.8	1,548	517	1,551	3,099
700	142.9	1,429	560	1,680	3,109
950	105.3	1,053	760	2,280	3,330
100,000	1.0	10	80,000	240,000	320,000

Table 28. Cost Sensitivity lo Example Problem (Wilson Model)

mathematical model can be constructed with reasonable ease (2, 3, 8, 10, 11, 13, 16, 17, 19, 21, 40).

In situations where the demand and/or lead time varies stochastically, the models used will resemble the deterministic Wilson Model, appended by a safety stock as shown in Figure 55. The safety stock (SS) is added to absorb or cushion the system during the periods when higher than average demand occurs. This safety stock can be used during these periods to satisfy the higher than average customer demand--for if this stock of goods were not available and a customer demand occurred, either the sale would be lost if the customer would not wait, or the sale would be backordered, that is filled from production occurring in the next cycle, with a loss in customer goodwill and additional records keeping costs.

The models used in analyses of this type can be applied in two steps. First, the lot size will be determined and second, from a knowledge of lead times, the safety stock will be determined. Two strategies for determination of lot size have evolved; one strategy is to make Q^* units of stock every time a manufacturing order is issued, the other is to make sufficient additional units to bring stock level up to some level (called S). The reasoning behind the two strategies is related to the uniformity of demand and the review policy. The
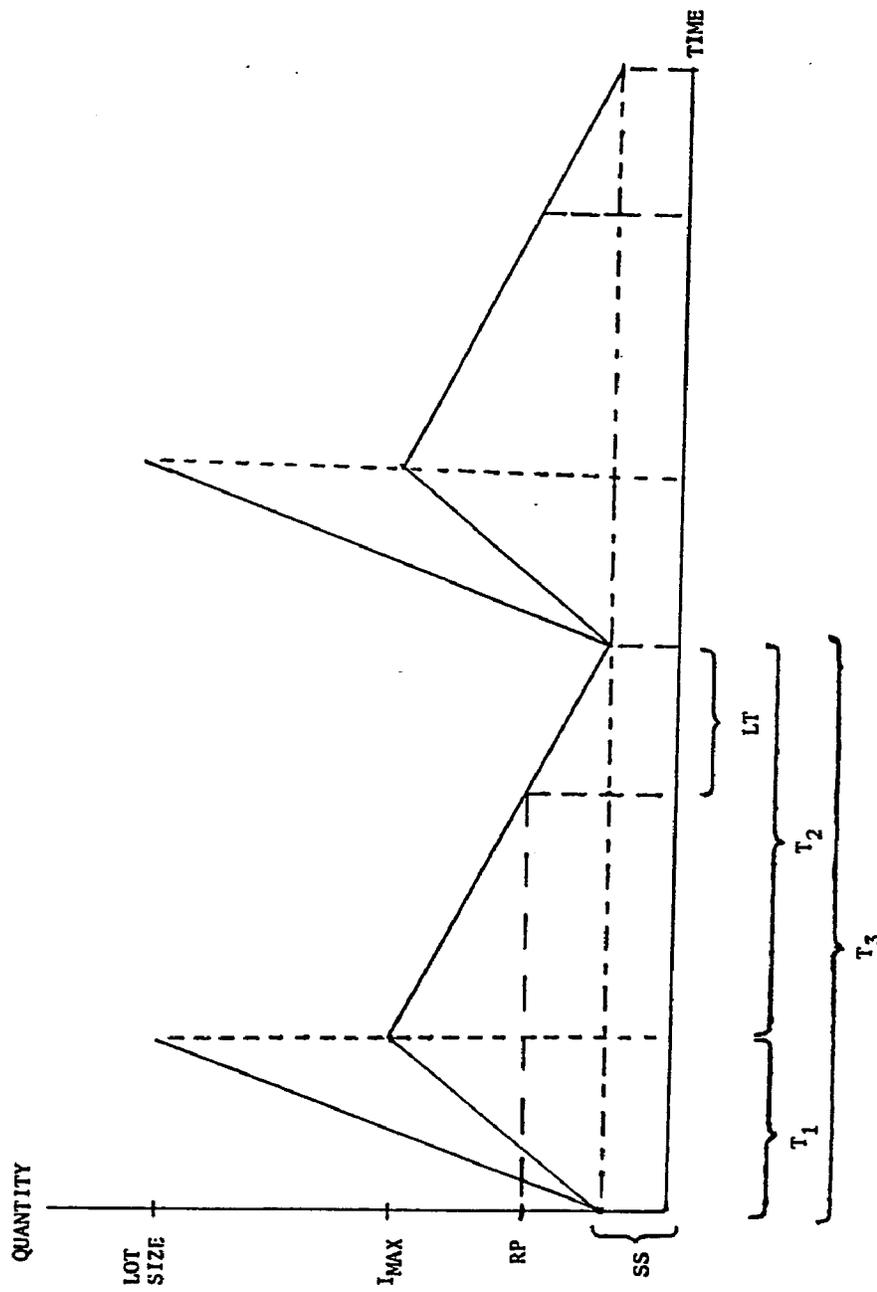
Figure 55. Single Product Manufacturing Lot Size Model with Safety Stock

can be calculated:

$$E(T_1) = Q^*/M$$

$$E(T_2) = (Q^*)(1 - E(D)M)/E(D)$$

If one uses these expected times to plan the duration and end of each cycle, one half of the time demand will be less than expected and inventory will be greater than expected and some demand will not be satisfied on demand. This unsatisfied demand is either lost, if the customers are not willing to wait for the product, or backordered and filled from the next period's production. Having unsatisfied demand will increase costs due to lost profit if customers will not wait or due to lost customer goodwill and additional records keeping cost if backorders are allowed.

This possibility of lost sales or lost goodwill is the basis for determination of the size of the safety stock. A safety stock (SS) of goods above expected demand must be held so that higher than average demand can be accommodated, increasing customer service. The cost of providing this cushion or safety stock must be balanced by the increase in customer service which occurs, that is, the cost of having dissatisfied customers that is avoided.

The optimum amount of safety stock that should be maintained is dependent upon the variability of demand,

Policy formulation under an (S,s) type of decision rule is, as previously stated conducted in two steps-- lot sizing and safety stock determination. The order up to quantity can be determined approximately by incorporating the consideration of the stochastic nature of demand into the Wilson Model and minimizing the expected total cost of setup and storage:

$$E(TC) = \frac{SU \int Df(D)dD}{Q} + \frac{Q(1 - \int Df(D)dD}{M} CC \quad (10)$$

where, f(D) is the probability density function
of demand,

all other symbols are as previously defined,

and E(·) is interpreted as meaning expected
value

But, Df(D) dD = E(D)

Substituting,

$$E(TC) = (\frac{E(D)}{Q})(SU) + Q(1 - \frac{E(D)}{M})CC$$

Differentiating as before, we obtain

$$Q^* = \sqrt{E(D)(SU)/((1- \frac{E(D)}{M})CC)} \quad (11)$$

which is the manufacturing lot size and the level to be ordered up to above safety stock level, that is S = Q* + SS. Using our expectation of demand, the expected manufacturing and usage portions of the cycle

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review policy may be a continuous or periodic review. When inventory is under continuous review, the inventory position (amount of stock on hand, in process, or on backorder) is compared to the reorder point after each inventory withdrawal for the item, and a manufacturing order issued for the item whenever the inventory position falls below the reorder point. Under a periodic review policy, the relationship of current inventory status to reorder point is checked at the end of each period of review and at these points in time manufacturing orders for any (and all) items below their reorder point are issued.

The existence of two lot sizing and two review policies can be combined into four distinct models. These models are the order up to a particular level, continuous review policy or an (S,s) policy where S is the maximum level to which inventory is built, and s is the reorder point; the order up to, periodic review model is also known as an (S,s) type policy; the order quantity models are known as (Q,s) type models. It can be shown that the (S,s) type policy is an optimal policy, and this model used as an illustration; for excellent development of the other policies. See Buchan and Koensberg (2), Johnson and Montgomery (8), Scarf et al (17), Taha (19) and Whitehouse and Wechsler (21).

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the cost of a stockout or backorder, inventory carrying cost, and the review strategy for inventory levels. Under the (S,s) type of policy with backordering, the optimum safety stock can be determined by minimizing the expected cost of the safety stock per cycle. The safety stock held is the amount of goods stored above the usage which is expected to occur during the lead time at the time of reorder or:

$$SS = RP - (LT(E(D))) \tag{12}$$

Letting $E(D) = (D)$ the expected demand during

the lead time,

the cost per cycle is

$$\text{Cycle Cost} = S \cdot U + (CC)\left(\frac{Q}{E(D)}\right)(Q + RP - \mu) +$$

$$B \int_{RP}^{\infty} (D - RP)f(D)dD \tag{13}$$

where

B is the backordering cost.

Differentiating with respect to RP

$$\frac{d(\text{cycle cost})}{d\ RP} = CC\ \frac{Q}{E(D)} + B\ (-F'(RP)) \tag{14}$$

where

F'(RP) is the complementary cumulative

distribution of D evaluated at RP

Rearranging

$$F'(RP) = \frac{(CC)Q}{(B)E(D)} \tag{15}$$

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and for any lot size Q, the reorder point should be
chosen so that the probability that demand will exceed
RP, that is, that the probability of a stockout will be
$(CC)Q/(SO)E(D)$. For a slightly better approximation
method and model for the lost sales case see Johnson
and Montgomery (8).

The following example will illustrate the above
result.

Let

$D \doteq$ stochastically distributed demand with
mean 400 units/day

SU = 10 \$/setup

M = 2000 units/day

CC = 3 \$/unit/year

LT = 2 days

B = 4 \$/backorder

using the Wilson Model,

Q^* = 646

therefore

$$F'(RP) \quad \frac{(3)(646)}{(4)(10,000)} = .005$$

so that the best reorder point is the one which will
give a .005 chance of stockout during the lead time.

If the lead time and demand both vary a distribu-
tion of demand during lead time may be built from
expirical data and this distribution used for F'(RP),
or the joint probability distribution calculated from

the two underlying distributions of demand and leap
time may be used. The latter procedure may be the more
difficult and if data is available, the former is the
recommended procedure (21).

Single Product - Varying Demand Model

While the stochastic models discussed above have
relaxed some of the restrictive assumptions of the
Wilson Model, they are not applicable in many situations.
These situations are ones in which data is non-existent
so that the requisite stochastic distributions cannot
be determined with any degree of confidence and ones
in which the demand varies from one period to the next.
The former situation will be discussed later in conjunc-
tion with the specific problem studied and the latter
will be addressed here. The varying demand may be a
seasonal pattern or be due to other factors but is
assumed to be known over the planning horizon.

The method used for finding the optimum production
plan for the product under the above conditions is the
Wagner-Whitin dynamic lot sizing algorithm (90). This
model minimizes the set-up and carrying costs as well
as the demand can vary from period to period. This
model is formulated as a forward recursive dynamic
programming problem for the tth period, $t = 1, 2, 3, \ldots N$

Let

D_t = Demand in period t

i_t = Interest charge per unit of inventory carried forward to period t + 1

SU_t = Set-up cost in period t

X_t = Amount of product manufactured

I = Inventory entering a period

I_0 = Initial inventory

Therefore in period t_1

$$I = I_0 + \sum_{j=1}^{t-1} X_j - \sum_{j=1}^{t-1} D_j \geq 0$$

If no backorders are allowed. The functional equation for the minimum cost policy can be stated as

$$f_t(I) = \min_{\substack{X_t \geq 0 \\ I+X_t \geq D_t}} \quad (i_{t-1})I + g(X_t)(SU_t) + f_{t+1}(I+X_t-D_t) \tag{16}$$

where

$$g(X_t) = \begin{cases} 0 \text{ if } X_t = 0 \\ 1 \text{ if } X_t \quad 0 \end{cases}$$

For period N,

$$f_N(I) = \min_{\substack{X_N \geq 0 \\ I+X_N = d_N}} \Sigma (i_{N-1})I + g(X_N)(SU_N) \tag{17}$$

and it is then possible to compute f_t for

t = N, N-1, ... 2, 1, and thereby obtain an optimal

solution.

Through development of several theorems about the characteristics of an optimal solution, a reformulation of the problem which makes it necessary to only consider subdivisions of the problem and still obtain optimal solutions is made:

Letting F(t) be the minimal cost program for periods 1 through t,

$$F(t) = \min \left[\min_{1 \le j \le t} \left[SU_j + \sum_{h=j}^{t-1} \sum_{k=h+1}^{t} i_h d_k + F(j-1) \right] \quad SU_t + F(t-1) \right] \quad (18)$$

where $F(1) = SU_1$

and $F(0) = 0$

This minimum cost policy for the first t periods is a set-up cost in period j plus the cost of filling demands D_k, k = j+t, ...t, via inventory carrying from period j, plus the cost of the optimum policy for periods 1 to j-1. With the formulation (12) above, for any period t only t policies must be considered in order to determine the optimum policy.

The number of policies considered in any period t, however, can be further reduced for

"If at any period t*, the minimum in equation (18) occurs for j = t** ≤ t*, then in periods t>t*, it is sufficient to consider only t**≤j≤t. In particular, if t* = t**, then it is sufficient to consider programs such that X_{t*}>0." (90)

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This is known as the Planning Horizon Theorem.

The Wagner-Whitin algorithm is stated as follows:

"1. Consider the policies of setting up at period t^{**}, $t^{**} = 1$, 2, $...$, t^*, and filling demands d_t, $t = t^{**}$, $t^{**} + 1$, $...$, t^*, by this order.

2. Determine the total cost of these t^* different policies by adding the set-up and holding costs associated with placing an order at period t^{**}, and the cost of acting optimally for periods 1 through $t^{**} - 1$ considered by themselves. The latter cost has been determined previously in the computations for periods $t = 1$, 2, $...$, $t^* - 1$.

3. From these t^* alternatives, select the minimum cost policy for periods 1 through t^* considered independently.

4. Proceed to period $t^* + 1$ (or stop if $t^* = N$). "

(90)

Wagner and Whitin have suggested the following tabular form (Table 29) for use in the solution of problems using their algorithm. In Table 29, the columns represent the time periods t, $t = 1$, $...$ N over which the algorithm is to be applied, and the period numbers constitute the first row of the table. The second and third rows are the ordering cost and demands for the N periods. The next set of rows are used for the storage of the costs of the possible policies that may be followed in period t. The notation used to show the various policies is the periods enclosed in parentheses and are the periods whose demands are considered to be filled by a setup in the earliest period in the

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Table 29. Notation for Wagner-Whitin Algorithm

Time Demand t	1	2	3	4	...	N
Set-up Cost	SU_1	SU_2	SU_3	SU_4	...	SU_N
Demand	D_1	D_2	D_3	D_4	...	D_N
$1, 2, ..., t-1)t$	1	(1)2	(1,2)3	(1,2,3)4	...	(1, 2, ..., N-1)N
$1, 2, ..., t-2)$ <u>t-1, t</u>		12	(1)23	(1,2)34	...	(1, 2, ..., N-2) N-1, N
$(1, 2, ..., t-3)$			123	(1)234	...	(1, 2, ..., N-3) N-2, N-1, N
$(1, 2, ..., t-4)$ <u>t-3,...t</u>				1243	...	(1, 2, ..., N-4) N-3, N-2, N-1, N
. . .					...	
Minimum cost Optimal policy $(1, 2, ..., t)$	(1)	(1,2)	(1,2,3)	(1,2,3,4)	...	(1, 2, ..., N)

parentheses and the periods that are underscored are the periods whose demand is satisfied by a setup in the earliest underscored period, e.g. (1,2)$\underline{34}$ is interpreted as the cost of satisfying the demand in periods one and two from the optimum manufacturing and inventory strategy calculated for period two plus the cost of satisfying the demand of periods three and four from a setup in period three and inventory carryover to satisfy the demand that occurs in period 4. There are t possible policies in any period t, however, through use of the planning horizon theorem, the number of policies which must be considered can usually be substantially reduced.

To illustrate the use of this algorithm the original example of Wagner and Whitin is reproduced. Table 29 contains the data used in this example, and Table 30 contains the results of the cost calculations of the various policies considered in each period.

To illustrate the calculations that produce the results in Table 31, the number of policies that must be considered in period one is one--that of setting up and producing sufficient product to fill the demand in period one. In period two, two policies (1)$\underline{2}$ and $\underline{12}$ must be considered: the former policy has a cost of 85 + 102 or the cost of setup in each period for that period's production, and the latter has a cost of setup

Month t	D_t	SU_t	i_t
1	69	85	1
2	29	102	1
3	36	102	1
4	61	101	1
5	61	98	1
6	26	114	1
7	34	105	1
8	67	86	1
9	45	119	1
10	67	110	1
11	79	98	1
12	56	114	1
Average	52.5	102.8	1

Table 30. Data for Wagner-Whitin Example

Month t	1	2	3	4	5	6	7	8	9	10	11	12
Set-up Cost	85	102	102	101	98	114	105	86	119	110	98	114
Demand	69	29	36	61	61	26	34	67	45	67	79	56
	85	187	216	287	375	462	505	555	674	710	808	903
		114	223	277	348	401	496	572	600	741	789	864
			186			400	469			734		901
							502					
Minimum Cost	85	114	186	277	348	400	469	555	600	710	789	864
Optimal Policy*	1	12	123	34	45	456	567	8	89	10	10, 11	11, 12

*Only the last order period is shown; 567 indicates that the optimal policy for periods 1 through 7 is to order in period 5 to satisfy D_5, D_6, D_7, and adopt an optimal policy for periods 1 through 4 considered separately.

Table 31. Results of Cost Calculations for Wagner-Whitin Example

in period one (85) plus a cost for carrying sufficient inventory into period two (29 x 1) to satisfy the demand in period two or a total cost of (85 + 29 = 114). All calculations are performed in a similar manner.

Some policies can be eliminated from consideration as an optimal policy. In our example, policies which would carry inventory into period four from either period one or two are non-optimal as the carrying costs for these policies would exceed the set-up cost in period four; i.e. a 1234 policy would have a cost of satisfying the demand in period four by carrying inventory of 61 units x 3 periods x 1 unit cost/period = 183 while a setup only costs 101. Extending this result, in any period t, t $\geq$ 4, policies calling for production in periods one or two to meet D_t can be eliminated from consideration (in terms of our table, the southwest diagonal can be truncated, thereby reducing the number of calculations that must be made).

For the set of data considered, the optimum policy calculated by working backwards through the table, is to set up in period eleven for D_{11} and D_{12}, period ten for D_{10}, period eight for D_8, and D_9, period five for D_5, D_6, and D_7, period three for D_3 and D_4 and in period one for D_1 and D_2. The total costs incurred with the policy is 864. This model has been extended by

Kaiman (55) and Karlin (56) for the case of stochastic
demand and its computational efficiency under certain
conditions improved by Silver and Meal (81) and Gleason
(39).

Multi-Product - Single Period Models

The major drawback to the single product models
is their failure to consider multiple products interac-
tions. The interactions which may occur are of two types:
the products compete for the limited productive capacity
of the manufacturing facility or the products may be
sequence dependent, that is the cost of setup may depend
upon the ordering or sequence of the production of the
products which are manufactured.

The multi-product single period models are rela-
tively easy to analyze. The basic notion in these
models is to determine if the particular set of products
for which manufacture is desired can be accomplished
during the period in question. This feasibility is
determined by if the sum of the required setup and
manufacturing time is less than or equal to the produc-
tion time available. Mathematically, this feasibility
constraint for a single machine may be expressed as

$$\sum_{i=1}^{N} S_i + \sum_{i=1}^{N} \frac{Q_i}{M_i} \leq C \qquad (19)$$

where
S_i = Set-up time for product i

Q_i = Quantity of product i to be produced

M_i = Manufacturing rate of product i

N = Number of products to be made

C = Productivity capacity of machine (time)

For a multiple machine problem the feasibility constraint can be expressed as:

$$\sum_{i=1}^{N} S_{i,j} + \sum_{i=1}^{N} \frac{Q_i}{M_{i,j}} \leq C_j \quad \text{for } j = 1, 2, 3, \ldots K \tag{20}$$

where

S_{ij} = the set-up time for product i on machine j

Q_i = the quantity of product i to be produced on machine j

$M_{i,j}$ = Manufacturing rate for product i on machine j

C_j = Productive time available on machine j

N = Number of products

A production schedule that violates either (19) or (20) above constitutes an infeasible production schedule. This infeasibility may be taken care of by either: increasing productive capacity by obtaining more machines or labor, or reducing the demand on productive capacity by incurring lost sales (not produce some of the desired items).

The trade-off of the cost of additional capacity versus the benefit (profit) associated with the extra

production that can be accomplished must be evaluated
to determine the best course of action. A heuristic
procedure that may be used to do this is to rank the
products to be produced on the basis of profit per
unit of productive capacity required and to produce all
products that have a profit per unit higher than the
cost of providing the productive capacity that the
product requires, that is if A is the cost of one unit
productive capacity up to current capacity and B is
the cost of one unit productive capacity above current
capacity, arrange the products on a profit per unit of
capacity required and produce all of the product that
can be produced with the current capacity whose contri-
bution to profit equals or exceeds the value of A,
plus any additional product that contributes per unit
of capacity provided more than the cost of providing
that production capability (B).

While violation of equation 20 in a multi-machine
situation is a sufficient condition for infeasibility,
feasibility in a multi-machine is not assured when
equation 20 holds. Infeasibility may result from the
sequence of operations that each product must undergo.
For example, if each of N products to be produced during
a particular production period undergoes more than one
operation and all of these products must go through
machine 1 before any other operation can be performed,

and equation 14 holds for machine 1 an an equality, not all products can be produced as no time remains in the period for the succeeding operations on the last product through machine 1. Such sequence constrained problems will not be discussed here, for more detail see any job shop sequencing discussion (3, 8, 10, 21).

Multi-Product - Multi-Period Models - Fixed Resources

The multi-product - multi-period models attempt to reflect most of the complicated interactions that are present in real world inventory problems. The objective of these models is to determine product production cycles which are within the capacity limit of the manufacturing facility. Four basic strategies evolve for determining these production cycles: evolve a repeatable schedule which has each product produced exactly once during the cycle and all products produced have the same length production-usage cycle, determine production cycles and use the strategies backlogging, allowing shortages (lost sales) or producing of products in periods earlier than needed to adjust for capacity constraints; adjust the productive capacity of the facility for each planning period via overtime, hiring, or firing to provide enough production capacity to manufacture all the products that are needed during the period, or to evolve a policy which combines the second and third strategies.

The necessity for adjustment of production-usage cycles of the products to the same or the fundamental cycle length can be illustrated by the following example. Suppose that the following parameters apply to the two products a particular facility manufactures on the same equipment and the Wilson Model assumptions hold.

Product A	Product B
SU = 10 \$/setup	SU = 20 \$/setup
D = 100,000 units/year	D = 10,000 units/year
M = 500,000 units/year	M = 20,000 units/year
CC = 3 \$/unit/year	CC = 8 \$/unit/year

Table 32. Data for LaGrange Example

Solving for Q* using the Wilson Model:

$$Q*_A = \sqrt{(100,000)(10)/(1 - .2)3} = 646$$

$$Q*_B = \sqrt{(10,000)(20)/(1 - .5)8} = 223$$

The manufacturing, usage and cycle time are

$T_{1,A} = 646/2000 = .323$

$T_{1,B} = 223/80 = 2.78$ days

$T_{2,A} = (646)(1 - .2)/400 = 1.29$ days

$T_{2,B} = 223(1 - .5)/40 = 2.78$ days

$T_{3,A} = 1.612$ days

$T_{3,B} = 5.56$ days

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and the interaction of these products as they compete for
the shared equipment can be observed by plotting the
time of manufacturing requirements as shown in Figure 56
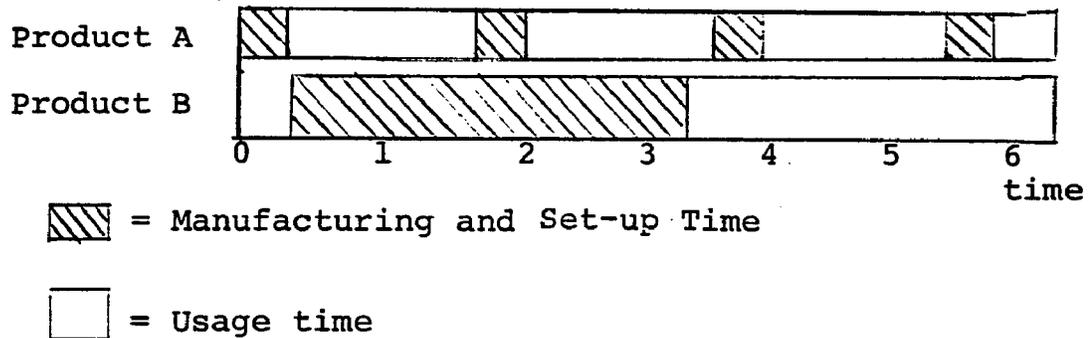below:

= Manufacturing and Set-up Time

= Usage time

Figure 56. Manufacturing Time Interference in
Unconstrained Two Product Case

As can be easily seen from Figure 56, unless the cycle
times match and the total manufacturing and set-up times
for all products are less than or equal to the cycle time
the production schedules dictated by the Wilson Model
will be infeasible requiring the equipment to produce
two different products simultaneously or more than its
capacity.

A methodology which can be used to adjust the Q*
in these multi-product situations in the incorporation
of this equal cycle time constraint into the Wilson
Model to assure that no cycle length conflicts arise.
This formulation would be

$$\min(TC) = NSU_i + \frac{D_i}{N} (1 - \frac{D_i}{M_i}) CC_i \qquad (21)$$

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where,

> N = Number of cycles/per year for all products
>
> SU_i = Set-up cost of product i
>
> D_i = Yearly demand for product i
>
> M_i = Yearly manufacturing rate for product i
>
> CC_i = Carrying cost for product i
>
> TC = Total cost

differentiating as before,

$$N = \sqrt{\frac{\sum_i D_i(1-D_i/M_i)CC}{\sum_i SU_i}} \qquad (22)$$

using the example data

$$N = \sqrt{\frac{(100,000)(1-.2)(3) + (10,000)(1-.5)(8)}{30}}$$

$$N = 96.6 \text{ setups/product/year}$$

and

> $Q^*_A = 1035$
>
> $Q^*_B = 104$

The use of the above modification of the Wilson
Model, while it does aid in determination of feasible,
optimum solution under the assumptions upon which it is
based, it may not be a global optimum in a three or
more product case. In that a better plan in a situation
of a large number of products are produced may be one
in which certain products are best produced only every
other or every third cycle (or less). Doll and

Whybark (31), and Ferreira and Hodgeson (37) have
extended this concept of finding a fundamental cycle
time and with the frequency which each product should be
produced for the single and multiple machine cases
respectively. The determination of the optimum cycle
time has also been addressed by Krone (57) and
Szendrovits (85).

The special case of determination of the relative
frequencies with which items that can be jointly
replenished, that is products manufactured on the same
setup but packed in different sizes or under different
names, has been studied to determine a fundamental
production frequency for the product and the frequency
with which each different size or brand should be
produced by Goyal (41, 42, 43), Nocturne (69), Shu (78),
and Silver (79, 80). The question of whether or not to
order an item when one with which it can be jointly
produced has been studied by Curry (22) and Churn(21)
who have studied "can order points"--that is, that
inventory level, below which the item can be economically
restocked, given that another item which uses the same
setup must be made, even though the reorder point has
not been reached.

An alternative to the repeatable schedule approach
to solution of the multi-product, multi-period problem

is to divide the planning horizon into periods and determine a feasible schedule (one that does not violate any capacity restrictions) for the production of the desired products. The construction of the feasible schedule is accomplished either by determining the unconstrained optimal solution and making this feasible or to rank the products to be produced and placing them on the schedule consistently with this ranking.

An unconstrained optimal solution to the problem can be obtained by using the Wilson Model to determine the lot sizes and by considering starting inventory levels, and the manufacturing and demand rates, determine when the goods should be produced, that is, the period in the planning horizon in which the goods will be manufactured. The period production requirement could also be determined by summing the period production requirements that would be generated by applying the Wagner-Whitin algorithm to each of the products (or at least those for which the assumptions of the Wilson Model do not hold). Either of the above procedures will usually yield periods in the planning horizon in which the productive capacity will be exceeded by the production requirements. This infeasibility is removed by either producing some goods before they are needed and/or backordering some of the needed goods until later

periods. The methods for removing them are usually heuristic, ranking the products in the periods which have production requirements exceeding productive capacity in increasing order of holding cost and/or storage costs. Products are then moved forward or backward in the planning horizon until either a feasible solution is obtained or the capacity of each period is allocated and lost sales or other strategies must be used to generate a feasible solution.

The above procedure can be quite time consuming and does not assure that an optimum production plan will be found. Improvements over the above method can be obtained by building the production schedule by starting with a trivial (no production) solution and adding production to the schedule in a manner that each addition to the schedule will represent the largest improvement in the schedule. Dynamic programming has been suggested for this type of analysis by Jensen (51) and Swoveland (84), however, these are highly complex and require large amounts of computation effort. A linear programming solution has been formulated by Manne (62) who aggregated similar products into classes to reduce the dimension and computation involved in solution; this linear programming approach has been improved by Kortenek, Sodard, and Soyster (58) who

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schedule in order of decreasing setup to demand ratios
and reduce the dimension and computation required.
Branch and bound and network formulations have been
suggested by Elmaghraby (36), Schwarz (75, 76),
Andres and Emans (23); and Dorsey, Hodgeson and Ratcliff
(32) and Zangwill (96, 97, 98).

Multi-Product - Multi-Period Models - Variable Resources

The multi-period, multi-product, variable resource
models are those that most accurately reflect the real
world; for the restriction of the fixed resources
assumption is relaxed. In many situations, the
productive capacity of the manufacturing facility can be
modified by working overtime or hiring or firing workers.
In cases where the amount of work or production varies
over the planning horizon, it may be more economical
to hire more laborers or work overtime during the
periods when high productive capacity is required than
to produce some of the goods required during these
periods in an earlier period and carry them in inventory
until needed. The models that attempt to balance the
costs of changing productive capacity and inventory
carrying costs are known as aggregate planning models.

These aggregate planning models may be formulated
mathematically or heuristically. If the costs of
hiring, firing, etc. are assumed to be linear, a linear

programming approach may be taken. This approach has
been taken by Manne (63) and Kortanek, Sodard, and
Soyster (58). The solution of aggregate planning models
by this method requires a great deal of computational
effort and is not computationally feasible for large
numbers of products and periods in the planning horizon.

Holt, Modigliani and Simon (49) and Holt (50),
make use of a linear approximation to portions of the
cost functions which they assume to be quadratic. The
form of this model is to minimize the period costs over
the planning horizon:

$$C_N = \sum_{t=1}^{N} C_t \qquad (23)$$

where

C_t = the costs for period t

and

$$C_t = (C_1 W_t) \qquad \text{Payroll costs}$$

$$+ C_2(W_t - W_{t-1}) \qquad \text{plus changes in capacity costs}$$

$$+ C_3(P_t - C_4 W_t)^2 + C_5 P_t - C_6 W_t \quad \text{plus overtime}$$

$$+ C_7(I_t - C_8 - C_0 S_t)^2 \qquad \text{plus inventory costs}$$

subject to

$$I_{t-1} + P_t - S_t = I_t \quad t = 1, 2, 3, \ldots N$$

where

W_t = Workforce in period t

P_t = Production rate in period t

$C_4 W_t$ = Maximum regular time production rate in period t

I_t = Inventory in period t

S_t = Order rate during period t

C_2 = Cost per unit change in capacity

$C_8 - C_9 S_t$ = Optimum inventory (unconstrained) period t

C_7 = Cost of storing one unit of inventory

All other constants and term are for fitting of curves.

The method for obtaining the aggregate planning solution (work force decision) is to differentiate equation 17 with respect to each decision variable. For a more detailed explanation, see the original article (49) or Buffa and Taubert (3).

O'Malley, Elmaghraby and Jeske (70) have suggested a combination method for aggregate planning. Their method is to use a summation of the lots determined for individual products using the Wagner-Whitin model as production requirements in each period and then smooth production via a linear programming model. This approach offers a "double smoothing effect"; it, however, still retains most of the computational difficulties associated with the linear programming models.

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