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The Development and Application of a Demand-Based Scheduling Heuristic for Paper Cutting Processes

by

Robert D. Mallon

A Thesis

Presented to the Graduate Committee

of Lehigh University

in Candidacy for the Degree of

Master of Science

in

Industrial Engineering

Lehigh University

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12-21-94

Date

Thesis Advisor

Department Chairperson

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Abstract

This thesis is concerned with the development of a system to provide scheduling information for use in a continuous production facility. The effect of schedules upon multiple evaluation criteria is considered. In particular, the relationships among the costs of meeting a promised delivery date, holding finished goods inventory, and minimizing machine setup time are examined. The system was tested with the specific production characteristics of an operational company. This company partitions bulk paper rolls into various sheet sizes, and has needs typical of businesses who are attempting to guarantee a high next-day fill rate on their various products.

In realistic factory settings, efficient algorithms for complex processes must balance goals that are often conflicting. Simplification to a single evaluation criteria may not be prudent considering the characteristics of the resultant schedule. Although the proposed system does not guarantee optimality, it provides a method to investigate scheduling effects upon several criteria. This system shows significant improvement over the company's current scheduling arrangements. Experiments were performed to tune system parameters.

The primary scheduling technique is known as the Days-of-Demand (DOD) ratio, which sets a priority level for a product based on how quickly its inventory will run out. However, scheduling decisions also include a second

level which is based on constraints that arise from operational factors. Specifically, this consists of a search procedure into future orders which is necessary to fulfill material requirements of bulk raw goods.

Innovation was possible through the formulation of scheduling logic, the investigation of multiple criteria, and tuning operations to analyze parameter settings. The algorithm was tested on order data from the factory to help determine necessary revisions.

Chapter 1

Introduction

A heuristic method was designed to generate practical schedules based on urgency and multiple evaluation criteria. It was specifically applied to the needs of a paper sheeting factory where large rolls of paper are cut to sizes requested by customers. However, it can be generalized to other industries where new scheduling methods are needed based on cost and prompt delivery. Basic objectives of the system are as follows:

Responsive Scheduling Characteristics

Computer Assisted

Technically Feasible

Economically Sound

A responsive system is one that can adapt to incoming orders or changes in system constraints in a timely and accurate fashion. In this system, this will occur by guaranteeing accurate sequencing of orders. Such a sequence is one which represents desired products in an arrangement which makes sense according to the technical ability of the machines. It should be consistent in the provision of schedules which attempt to meet performance criteria defined by setup costs, inventory holding costs, and lateness penalties.

The system must be computer assisted because of the complex nature of the scheduling decisions made. Such a system can store all present orders, look into the future to determine the needs of upcoming time periods, observe the amounts of product in inventory, and fabricate a sequence that will consider a multi-tiered cost function. A human controlled, manual scheduling system cannot guarantee superior schedules because of the large number of variables which must be balanced.

Technically feasible means that the system can actually be installed and operated. Algorithm complexity should be examined to ensure that the program will run in a time period that is useful to the scheduling company.

An economical system provides a benefit to its user which outweighs its expenses. The system must provide a sound alternative to available techniques and systems. For example, one way this system will function is through its ability to balance production factors such as inventory levels and setup costs. Another potential benefit results from quicker product delivery.

The work performed consisted of reviewing current manual scheduling practices, analyzing desired system characteristics, and assisting in the development of the system which could provide the desired output. After the model was operational, system parameters were tuned to provide a sound scheduling strategy. The project was accomplished by balancing the potential of computing power with sequencing logic.

The resulting system can be viewed as a processor with various inputs and outputs and a certain functionality. One input consists of product order information. Another input is the current inventory levels and their rate of decrease. Some additional inputs include raw good information and the setup times which are a result of product variable changes.

The functionality of the system determines what types of manipulations are done to the string of inputs. Sequencing decisions are made based on the Days of Demand ratio and constraints due to physical production requirements.

System outputs consist of a sequence of orders, ready times and inventory levels. These results provide measurements of how the system is operating, such as fill rates and total setups. They allow analysis to determine good parameters and general trends toward established goals.

CHAPTER 2

Problem Description

The problem addressed in this thesis is the need for adaptive scheduling methods that consider multiple levels of important criteria. In many situations where lateness, inventory levels, and setups all add cost to the manufacture of product, only one of these factors is considered. Doing so can cause other costs to increase or produce impractical sequences in resultant schedules. Current competitive markets also demand adaptive scheduling methods to address production in terms of the urgency of particular items.

The corporation that inspired this scheduling system is involved in the production of paper. In particular, their facility cuts large bulk rolls of paper into the sizes needed by its customers; an operation known as 'sheeting'. The remainder of this chapter will explain the operation of the studied facility, which led to the examination of specific scheduling issues.

2.1 Factory Operation and Historic Methods

The basic production machinery of this plant consists of two sheeters; large machines that cut paper. These machines are identical in all respects. The only necessary raw goods which feed the machines are bulk rolls of paper, known as "parent" rolls. Output consists of sheets of paper of various sizes and grades. Up to five parent rolls can be cut at once depending upon the grade (thickness) of the paper. Demand at the plant is great enough to eliminate slack, or excess capacity, in any production schedule.

The studied facility produces almost 800 distinct items and receives approximately one hundred orders per day. A particular product is designated by its finish and thickness, known as the product type and basis weight. An example would be "Smith 80", where "Smith" is the type and "80" is the basis weight. Sheet dimensions are also requested when an order is placed. Orders with the same type and basis weight but having different dimensions can be cut from the same parent roll, but they incur a setup penalty.

Only one product type may be produced at any time. Production rates, which are related to the cutting speed of the sheeters, are deterministic and constant. Pre-emption, or removing a order before its processing is complete is not an option. Also, due to various physical constraints (which will be expanded in this chapter), large amounts of individual products must be produced at a time.

In the past, scheduling was dependent upon current factory conditions and order information, but there was no well-defined process to assist in these production decisions. The scheduling determinations were made manually by an individual who attempted to assess incoming orders and balance them with the sheeter's capabilities. When a customer order was received, the scheduler would examine the schedule for the next time that product was being made, insert the order into the product grouping (if there was room), and then add several days for shipment to determine a final delivery date. If there was not room in the next scheduled run of that product, the order would be scheduled last. This process resulted in an average delivery time of approximately three weeks.

In this setting, inventory levels were not considered. Not only were production decisions made independently of current levels, but they were not even systematically tracked by anyone in the company. Due dates also were considered to be unimportant. A due date was established by the company upon examination of upcoming production amounts. Customer service issues were not yet necessary in this market. Therefore, when scheduling, the operator's focus was on setup time. Within the limits of production capacity, the scheduler tried to sequence products that would result in low collective setup times. It can be said that setup time was the only and most important criterion used to control production scheduling.

2.2 Relationship to the Product Cycle

The relationship of the scheduling system to the corporation's enterprise model can be seen in Figure 2-1. In this diagram, the separate systems which are involved in translating an order, whether internal or external, into a finished product are displayed.

Production Scheduling consists of the specific sequencing and arrangement steps which are performed upon the various inputs. Directly related to this are the *Scheduling Parameters*, which, based on previous runs or desired schedule type, can be filtered back into scheduling through

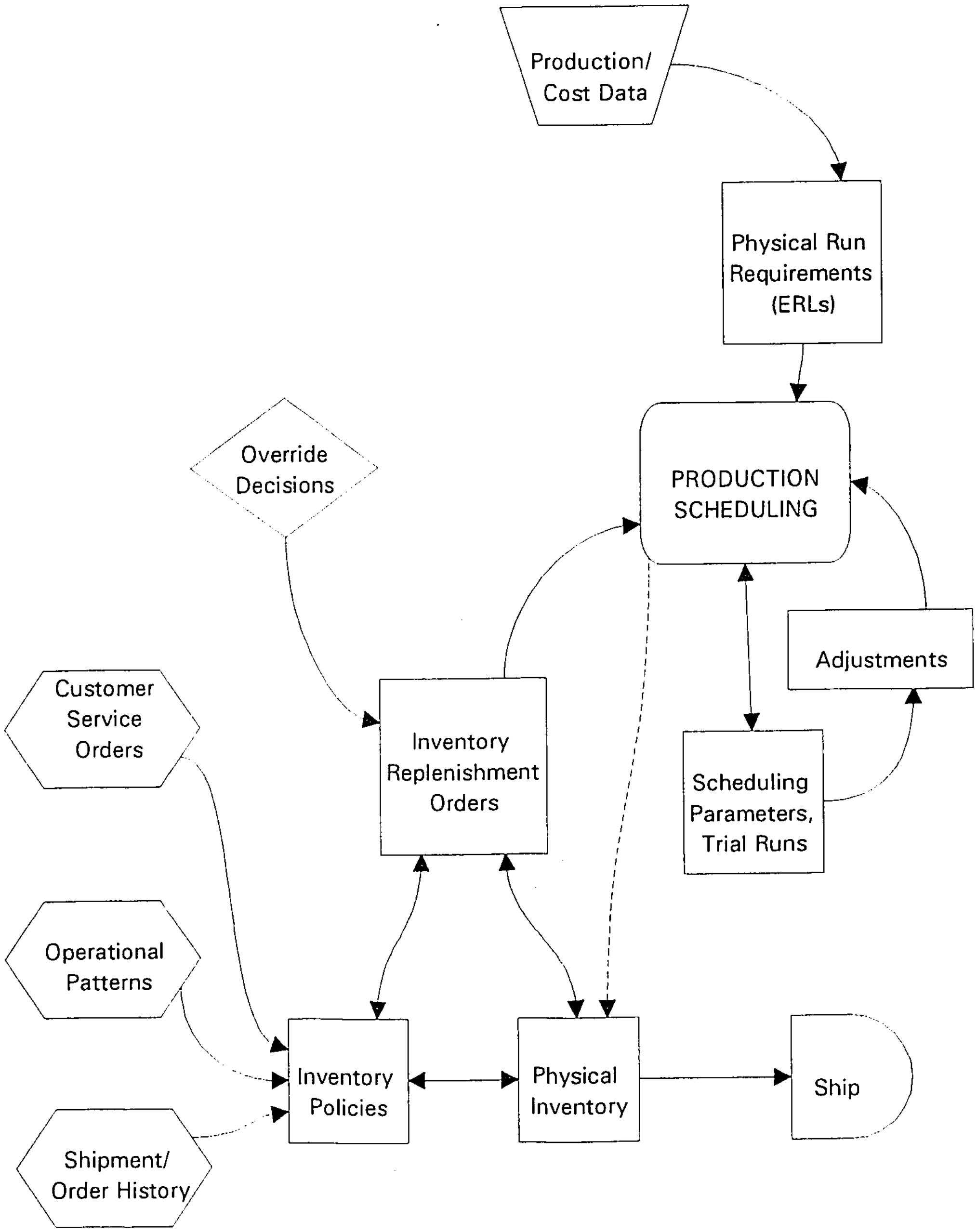


Figure 2.1
Enterprise Model

Adjustments. Physical Run Requirements, which are production constraints affect scheduling based on *Production and Cost Data.*

The inventory system is controlled by *Inventory Policies*. These are the set of rules that determine if there is enough product in inventory, or if more needs to be made. *Shipment and Order History* dictate the normal level of a particular good in inventory, while *Operational Patterns* represent forecasted demand for the future. *Inventory Policy* checks *Physical Inventory* to observe current levels and triggers an *Inventory Replenishment Order* if there is not enough. *Override Decisions* are possible based on urgent unforeseen orders. The connection between *Production Scheduling* and *Physical Inventory* in Figure 2-1 is dashed because the schedule may not always match actual production due to down time, etc. Finally, finished goods are *Shipped* from *Physical Inventory*.

2.3 Operational Characteristics

The studied company makes finished paper products for uses such as magazines and annual reports. The demand for such paper is not regular, but rather seasonal and random. It is not possible to forecast with accuracy the demand for any particular time period, so inventory levels must be balanced with machine resource capacity. The costs due to carrying inventory are proportional to their finished good levels.

The scheduling system does not need to consider this fluctuating demand in daily operations because it is only concerned with the current order list which is passed down from the inventory system. However, the effect of scheduling strategy upon inventory levels is still important. Enough finished goods must be held to meet strict customer service guidelines. Also, the effects of the carrying costs upon total schedule cost cannot be ignored.

Machine setups are another important characteristic of the operation of the facility. A setup, in this case, denotes the time spent changing various machine variables to cut a different size or grade of paper. However, setup time is sequence dependent, which means that it is dependent upon both the product that is presently being sheeted and the next product which will be scheduled. For example, if a different paper size must be cut, the sheeter must be slowed so that the cutting knives can be moved to their new locations. The knife settings are dependent upon sheet dimensions and therefore change when a new size must be processed.

Setups result in machine inactivity, and therefore, a lost opportunity to produce another item. Setup time should be decreased as much as possible while still considering the other scheduling criteria.

2.4 Parent Roll Constraints

A crucial constraint in the studied factory consists of the physical characteristics of the parent rolls which are loaded onto the sheeters. These rolls are approximately eighty inches in length, forty inches in diameter, and usually weigh between three and four tons. Once in production, a parent roll cannot be removed until it has been completely used. Because most orders are in the range of one to two tons, it is not feasible to produce a sequence of individual orders independent of their respective parent rolls. It is necessary to produce those items in the schedule that are made from the same parent roll together so that physical limitations are met.

This minimum production quantity has been named the Physical Run Requirement (PRR). It can be determined by multiplying the number of parent rolls which can be cut at once (between one and five) by the weight of the parent roll, and then by the percent yield of the production process.

$$PRR = Parent\ Roll\ Weight * \#\ of\ Rolls * \%\ Yield \qquad (2.1)$$

The percent yield is a constant based on scrap factors obtained from the operation of the sheeting machines.

This type of operation, involving bulk roll requirements and continuous cutting operations, is similar to photographic film manufacturing. A detailed study of this area was performed by Tsubone, et.al.(18).

This description of the studied facility outlines a problem where innovative scheduling can be of great benefit. Many of the desired system characteristics are not unique to this company, but rather are common goals in industry. This problem definition helps to determine system objectives and identify areas in which constraining factors might become important.

Chapter 3

Background Information and Literature Review

Production Scheduling as a scientific process was first investigated during World War II. After that point, many methods, both exact and heuristic, began to appear in literature related to Industrial Engineering, Operations Research, and Computer Science. Now there are entire textbooks devoted to the subject, as well as professional societies to promote this type of research. This chapter will show some solution techniques and how they provide a sound basis for this thesis.

3.1 Characterization of this Problem

It is necessary, first, to identify some characteristics of this problem as it fits into the accepted notation of sequencing and scheduling. Although several classification schemes are available, most are variations of the same theme with common syntax. The following is a summation of systems parameters, which were introduced in the previous chapter:

- One product will be produced at a time.
- There are multiple products.
- Products will be produced over multiple time horizons.
- Production rates are deterministic and assumed to be constant.
- Each product has an associated setup time which is sequence dependent.

- Carrying costs are proportional to inventory levels.
- Demand rates are stochastic.
- There are two servers which are identical and operate in parallel.
- Pre-emption of a product is not possible.

A problem in which there are multiple servers which are identical and in parallel is termed a single machine, multiple resource problem. (14) Some of the above terminology is adapted from that reported in Sen and Gupta (16). A further review of classification schemes can be found in Wah and Baumgarter (20).

This characterization of the problem helps to give a bound on the types of solutions which must be investigated. While those problems with identical attributes can provide intimate insight into solution possibilities, problems that are only similar are also useful for general strategies or parts that may be adaptable to the given problem.

3.2 Literature Review

This first papers in machine scheduling research appeared in the early 1950's in Naval Research Logistics Quarterly. The first of these is by Johnson (8), and is recognized as the seminal paper in scheduling. It involved the scheduling of two machines to minimize makespan of the orders which needed to be processed consecutively on both machines. (Makespan is the maximum time that any product spends in the system.)

In his paper published in 1954, Smith (17) mentions two strategies which still pervade this area as components of more complex scheduling algorithms. For a single machine problem, the Earliest Due Date (EDD) heuristic schedules items in nondecreasing order of due date. For n orders with due dates d, if:

$$d_{[i]} < d_{[i+1]} \; for \; all \; i = 1,n \tag{3.1}$$

then maximum lateness of all orders is minimized. The notation *[ ]* signifies the order of the sequence. Therefore, [2] designates the second item in a particular sequence, and $d_{[2]}$ designates the due date of that second order.

The Weighted Shortest Processing Time (WSPT) heuristic was also presented in Smith's paper (17). It minimizes weighted flowtime by ordering items according to the ratio:

$$\frac{p_{[i]}}{w_{[i]}} < \frac{p_{[i+1]}}{w_{[i+1]}} \quad for \; all \; i = 1,n \tag{3.2}$$

where p is an item's processing time and w is a weight associated with the order's urgency. The EDD and WSPT algorithms are still widely utilized, both on their own and as a component of more complicated designs.

Most scheduling models consider one criteria such as lateness or flowtime as the dominant factor affecting system performance. A review of single machine scheduling problems can be found in Gupta and Kyparisis (6). There are many other single criteria models available, which can be effectively applied when a system only requires that type of consideration.

Multiple criteria models have also been widely studied. These models deal with situations where one type of schedule cost will be driven higher in an attempt to minimize another. For example, minimizing lateness can cause the number of setups required between products to increase. There are many bi-criterion strategies and a growing number of algorithms that take more than two objectives under consideration. MacCarthy and Liu (12) outline the gap between theory and practice in scheduling literature. They mention that a recent trends have attempted to fill in these gaps, and particularly designate multiple-criteria models as one of the most important areas. Sequence dependent setup times are noted as one of the most common complications.

Formulation of multiple criteria problems can be done in several ways, as outlined in Liao, Huang, and Tseng (10). The first is to define a weighted objective function which combines the separate criteria by weighting the various factors relative to one another. The second is to establish one criteria as the objective function, and translate the others into constraints. For example, if the minimization of flowtime and lateness was desired, the objective function would minimize flowtime and a constraint would be constructed that required all due dates to be met.

Fry, Armstrong, and Lewis (5) performed a survey on single machine multiple objective sequencing research. Solution methods vary depending on particular objectives. However, two general approaches seem to pervade many solutions. The first is the formation of an efficient frontier of solutions, where an efficient solution represents an acceptable solution for a given situation. A good schedule must be chosen according to the goals of the individual who schedules. The same efficient frontier may provide different solutions for two different locations, dependent upon present conditions. The second approach is to utilize a technique such as branch and bound to minimize the weighted objective type of function.

In formation of an efficient frontier, enumeration of a number of feasible schedules is necessary. Bernardo and Lin (3) studied a situation where minimum tardiness and setup costs were desired. They use an interactive approach, where the decision maker needs to reduce the number of feasible schedules to a quantity where an informed decision can be made. Again, such a method is based upon the local preferences of a particular setting. It also usually can only deal with a small number of jobs (< 20 jobs).

The capacitated lot sizing problem inherently has multiple objectives, as it involves the balance of production, setup and inventory costs in an attempt to provide standard production quantities. Lotfi and Yoon (11) presented an algorithm for a situation with multiple time periods and time varying demand. However, such demand was also deterministic, unlike that of the conditions outlined for this thesis.

A study which involved conditions much like those of this thesis was found in Leachman and Gascon (9). They were responsible for scheduling a multi-item, single machine production system with varying demands. Scheduling criteria involved were inventory levels and economic production cycles, as they are in the present problem. They also noted a lack of investigation in this area in the academic literature. Their solution was based on the traditional economic lot sizing problem (ELSP), which formulates repeating product cycles which contain a fixed amount of each product. The ELSP fails to account for variations from forecasted demand rates, which leads to stockouts. Their alteration of this policy involves subtracting a small amount from all production runs in a cycle, which allows the problem item to be made soon enough to avoid a stockout.

A somewhat different viewpoint on scheduling logic was made by Vergin and Lee. (19) They state that "No single scheduling rule can be termed the best, but rather a scheduling rule should be tailored to the particular system to be scheduled." Such a rule should be dependent not only on one performance criterion, but the number of products, their demand distribution, carrying, setup, and shortage costs, and the utilization of resources. Vergin and Lee (19) evaluate several decision rules as they perform on identical problems. They were compared to the classical lot sizing model, both with and without stockout costs. One of these rules was proposed by Magee and Boodman, (13) who compute a maximum proportion of demand which should be made once a product has started processing. It is as follows:

$$a_i = \frac{2R_i(1-R_i/P_i)}{\sum_i R_i(1-R_i/P_i)} \qquad (3.3)$$

In this equation, R equals demand rate per year, while P is the production rate per year. The product will continue until another item stocks out or the ratio

a_i is reached. At that time, production will switch either to the product which has stocked out, or to that item with the lowest ratio of inventory to average usage. The other decision rules involved alterations of this rule, including setting a maximum production amount, and allowing backorders. The most successful rule was a combination of ELSP and the production of items with less than a fixed minimum number of days usage on hand. This strategy correlates to the DOD ratio, although implementation occurred in different circumstances. These various rules all tended to operate better than the classic ELSP method.

Tsubone et. al. describe a scheduling system for a plant which produces photographic film (18). It is very similar to a paper sheeting facility in that large rolls of film are cut into various smaller sizes for end use. Also, many end products are made from each bulk roll, so demand for the bulk roll is fairly stable compared to the products. It also mentions the problems of filling more than one order from a single bulk roll and proposes a way to do so. After an order has been scheduled for production, the remaining bulk roll amount is calculated. Products that can also be made from that particular bulk roll will fill the remaining capacity of the roll. This aggregation notion for similar jobs will become particularly relevant to the studied company when attempting to fill the capacity remaining on parent rolls because of physical run requirements. Solution methodologies beyond this are not relevant, however, because they involve a second stage of production.

Issues of computational complexity are discussed in Parker and Rardin (15). It is mentioned that because a problem belongs to the class NP, it cannot be proved that a polynomial time algorithm can be found to solve it. NP stands for Non-Deterministic Polynomial Time Algorithm, which signifies that some problem instances require total enumeration of all solutions to determine the optimal solution.

Justification for using heuristic solutions (priority rules) for scheduling problems is also detailed by Cheng and Sin (4). They suggest simplifying a multiple machine problem by considering the system as an aggregated facility. This view of one machine rather than two or more might make an algorithm simpler, but can lose sight of the performance of the individual machines.

The issue of sequence dependent setup times has been widely studied, yet it remains an obstacle to generating good sequences. This is often because it is only an embedded part of a larger problem. The one machine, multiple product scheduling problem with sequence dependent setup times is actually a traveling salesman problem. Several solution methodologies are discussed in Haynes, Komar, and Byrd (7).

The use of rolling horizon scheduling is detailed by Baker and Peterson (2). A rolling schedule solves for multiple periods into the future, but only implements the first of these periods. It is then rerun at the beginning of the next period. Baker and Peterson describe a rolling schedule as "...the practical means that analysis is converted to action in dynamic schedules" (2). The effectiveness of the rolling schedule was investigated by Baker (1). He stresses the difference between the model and the system, stressing that the model tries to optimize over a limited horizon. The system needs to work in practice, and the information it relies upon is both uncertain and limited. His paper examines the effectiveness of using a rolling horizon to negate the effects of decisions made which are based on this indefinite information.

Those techniques presented by Leachman and Gascon (9), as well as those of Vergin and Lee (19) provide suggestions which are particularly helpful in algorithm development. Their methods are based on the difficulties caused by stochastic demand and its impact upon other scheduling factors. The study of Tsubone, et.al., (18) suggests methods to deal with hard constraints when testing an algorithm in a continuous production facility with bulk roll requirements. These references provide a sound basis for inquiry into new scheduling methods. The techniques that have been used in the past also underline the areas that scholarly research has emphasized, as well as those where there likely is room for further innovation.

Chapter 4

Analysis

This chapter details the analysis of system characteristics and investigation of various techniques which might impact system components. Such an evaluation will highlight those areas where emphasis should be placed and help ascertain where limitations may occur.

4.1 Multiple Evaluation Criteria

In many practical cases, the effect that one evaluation criteria has on the 'quality' of the final schedule dominates all others. For example, a company may want to guarantee on-time delivery at the expense of all other operational measures. Therefore, during formulation, it is feasible to attempt to minimize the dominant criteria, while ignoring others. The optimization of one criteria is justifiable because other criteria have such a small impact in comparison to that dominant factor.

In other systems, minimization of one criteria causes other related measures to behave inversely, driving overall schedule quality negatively. This type of interaction is evident in the studied company. They cannot simply minimize inventory cost because that would cause an increase in late orders for high volume products. Due date satisfaction cannot be the only goal because it causes an increase in setup times between individual products.

In such a situation, approaches which consider more than one criterion must be appraised. Minimization of setup and inventory costs are important goals, in addition to due date satisfaction. Their aggregate effects need to be measured in a way that equalizes their differing units. In this case, a weighted cost can be assigned with the desired effect.

The origination of cost measurements can also be questioned, however. In the studied company, a lateness cost was assessed that represents a percentage of the sale price of a product. In the future, it may be necessary to alter that figure to account for increased pressure to meet due dates and provide higher customer satisfaction. Therefore, evaluation of several levels of these variables would be valuable in assessing system operation under different settings. In some of these cases, certain criteria might become insignificant in comparison to others, and scheduling results might have different implications.

Having defined the various factors that impact scheduling decisions, a mathematical function to measure system performance can be expanded.

$$\begin{aligned} \textit{Minimize} \quad & a \textstyle\sum_i L_i & & i \in (1, \max \textit{order} \ \#) \\ & + b \textstyle\sum_j \sum_k X_{jk} S_{jk} & & j,k \in (1, \max \textit{order} \ \#) \\ & + c \textstyle\sum_n I_n & & n \in (1, \max \textit{product} \ \#) \end{aligned}$$

where a = Lateness cost penalty

b = Setup cost penalty

c = Inventory carrying cost

L_i = 1 if order i is late, 0 if not

X_{jk} = 1 if there is a setup between order j and order k,

0 if there is not

S_{jk} = Setup time between order j and order k

I_n = Amount of product n in inventory

The evalution function represents the aggregate effect of the three criteria which have been designated as important. The first line is the number of late orders multiplied by a constant *a* that represents average lateness cost. The second line is the number of total setup minutes multiplied by a setup penalty, *b*. The third line is the amount of pounds in inventory of a particular product multiplied by the holding cost, *c*. The summation of these three cost categories gives a total cost for a particular schedule. There were several assumptions made to use this function:

1. An average late cost for different product types is used to simplify assessing lateness penalties.

2. Setup costs are dependent upon setup time, which is a representation of a lost opportunity to produce another item.

3. Holding costs are identical for all products.

This evaluation function provides appropriate goals for scheduling methodology and decision making.

Because there are two sheeting machines, this problem would normally involve two levels of scheduling decisions. The first would be an assignment of each product to one of the sheeters, dependent upon characteristics of the orders and the hardware of the machines. The second level would then consist of the sequencing of those products, once they are assigned to a particular machine.

However, in this case, both machines are identical in every way. Also, when considering fulfillment of PRR requirements, it is important to be able to consider all orders, not just those that have been assigned to one of the machines. It would not be wise to run two related jobs on the separate processors because they could be run consecutively on one machine, resulting in less setup time and a tighter sequence. Therefore, it was assumed that the two machines could be equated to one processor with double the capacity. Assignments could then be made after the basic sequence was produced, gathering items which could help to lower collective setup times.

The one machine, *n* job problem with sequence dependent setup times has been shown to be NP Hard (15). This problem is imbedded within the studied facility, in addition to other restrictions and considerations. Therefore, the thesis problem is also NP Hard. Due to these factors, heuristic methods are a valid strategy for the solution of this type of problem.

A heuristic method allows decisions to be made at points of uncertainty in system operation. Every possible combination of variables does not have to be considered, but rather, a good decision can be made considering various system attributes. Using such a heuristic for this type of problem may provide a practical alternative for determining production sequences that retain desired operational characteristics.

4.2 Inventory Considerations

New customer service requirements often require that product be delivered in a short time frame. This urgency must be considered in scheduling strategy, which in turn is affected by inventory policy. The finished good levels which are kept by a company in inventory will dictate where an order originates.

One possibility is to fill demand immediately by keeping very high levels of all products in inventory. All incoming orders are filled from finished goods, and the machines are used solely to replenish inventory. However, this results in massive holding costs which offset any customer service benefits gained by the new delivery policy. There also may be issues of spoilage if goods are stored too long.

Another option is to fill orders directly from the production machines, which minimizes holding costs. The sequence of orders mimics the incoming order requests, dependent upon their priority. This strategy also has its drawbacks as it results in a excess of setup periods when the machines can not be utilized. It also results in unmet demand in busy periods due to capacity constraints.

A third policy involves keeping enough inventory to fill products with high variable demand, yet trying to meet as many of the incoming orders as possible directly from the machines. This strategy has more balance. However, it is also more difficult to achieve as it involves the tracking of inventory levels as well as production of urgent orders. This inventory policy, which attempts to balance the previous two methods was one of the major catalysts for using the Days of Demand ratio.

4.3 Constraint Based Scheduling

In many systems, constraints on production sequence are present that preclude the use of various approaches. The physical structure of either raw goods or final assemblies force production in groups or batches, not just for an outside criteria such as setups, but because there is no other way for manufacturing to occur. Sequencing individual products might be considered independent of these constraints, but the final ordering would be substantially altered from its expected outcome.

In the studied company, such constraints were present because of the nature of raw goods or 'parent' rolls of paper. An individual order might only use a small portion of a roll. However, once a roll is put into production, it can not be removed until its capacity has been depleted. Therefore, the rest of the roll must be used, to either produce extra product, or to make other products which also use that roll. In either case, sequencing is no longer dependent on just a simple evaluation criteria, but also upon the individual product's Physical Run Requirements.

To emphasize this effect, other methods were examined for their usefulness for system goals. When pitted against this physical constraint, however, it became apparent that the desired effect is lost in transformation.

For example, assume Earliest Due Date (EDD) has been chosen to minimize maximum lateness. The simple sequence that would result from ordering product in EDD progression would be confounded when it became apparent that the second product sequenced would not actually follow the first, but rather follow all the other products which are made from the remaining capacity of the parent roll of the first. In addition, the third and fourth products might leapfrog over the second, because they can be made from the same parent roll as the first. The final sequence which results from alterations made because of physical constraints would appear little like that of the original EDD order.

Utilizing another heuristic, such as Shortest Processing Time (SPT) could also have little utility in this setting. Processing times would not simply be a function of individual products, but rather of their parent roll size. Although minimizing flowtime might have been the original goal, the SPT sequence would be confounded by these other factors.

Therefore, the scheduling system must keep physical issues under consideration. The formulation of the system must account for parent roll capacities, the products that will fill them, and a method to produce a good sequence under these conditions. Constraints must be considered as a factor in every scheduling step.

4.4 Economic Factors

Another important factor affecting scheduling decisions is the economic impact of production quantities. In the case of known demand, the classic Economic Order Quantity (EOQ) model is one guide to the size of a product run which should be made. This model attempts to balance inventory costs with lost opportunity cost caused by setup times, and is based on periodic product demand.

In most cases, and in the studied company, however, demand is not constant. An average demand can be computed for each individual product based on historic data, although this might introduce error into the equation. This average demand is then used to produce an approximation to the EOQ model, which in this case is called an Economic Run Length.(ERL) It must be realized that this ERL will only be an estimate and should not be the only factor in determining production quantities.

In the studied company, the ERL is a large number for most products because of high demand. It is, in most cases, several times the size of the Physical Run Requirements resulting from parent roll considerations. As previously emphasized, production quantities are again impacted for reasons other than the basic criteria of minimizing setup, holding, and late order costs. The ERL, in actuality, combines setup and inventory factors in an attempt to minimize both. While Physical Run Requirements are hard constraints, ERL quantities are only a guideline.

The ERL and PRR amounts are very rarely multiples of one another, which creates the need for a method to determine the proper production quantities based on the two conflicting numbers. Also, because the ERL is an approximation, scheduling options should be available which are not dependent upon it. The difference between the schedules will verify if the ERL has a significant effect and if that effect is positive.

4.5 Grouping Techniques

Sequence dependent setup times have been mentioned as one of the component portions of this scheduling dilemma. However, Physical Run Requirements again have an impact, as they preclude many sequencing decisions from being made. A means to lower these dependent setup times after PRR amounts have been determined is necessary.

Although there are two machines that must be sequenced, the system will be viewed with one processor with double the capacity. If assignment was necessary before sequencing, product would be split fairly evenly between the two machines. However, some groupings might become infeasible because product would only be resident on one machine. This would also preclude using some orders to utilize remaining capacity from Physical Run Requirements. If products were assigned accoring to low sequence dependent setup times, an imbalance might occur because of the high demand for certain products. In particular, one sheeter might become crowded while the other is starved.

Assignment needs to occur after physical constraints have been considered and grouping has been performed. In this manner, groups that had been formed to take advantage of PRRs or low setup times could remain together and be assigned collectively to one of the machines.

Analysis of the needs of this scheduling system outlines those areas where effective innovation might occur, as well as setting guidelines which will allow for productive results. Considering multiple evaluation criteria, physical constraints, inventory issues, economic factors, and grouping techniques all add to the feasibility of the system.

CHAPTER 5

System Design

This chapter will detail the methods which were used to transform desirable system characteristics into functioning operations. The scheduling system can be described as a processor which, given a series of inputs, performs certain functions on them, and results in specific outputs. This is represented in Figure 5-1.

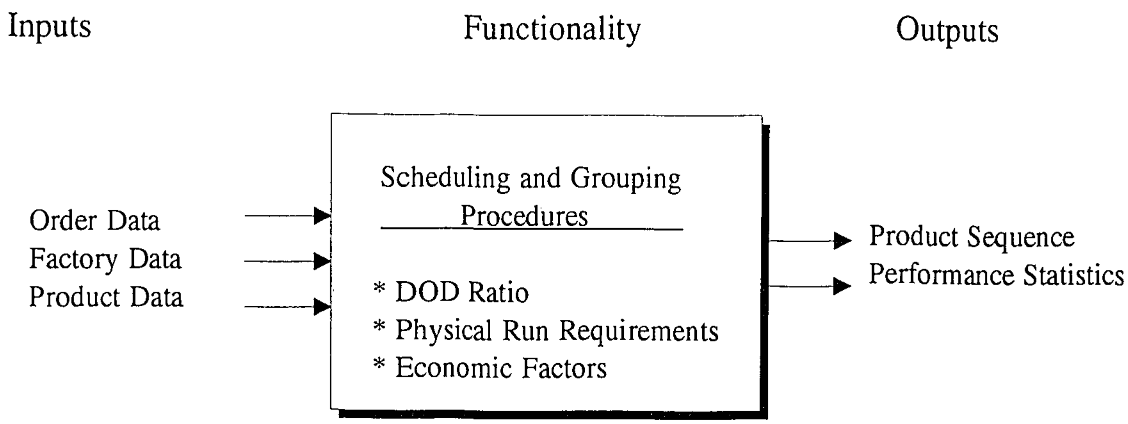
It is necessary to clarify some of the notation that will be used in this section. The term Stock Keeping Unit (SKU) is used to denote a particular product with unique attributes of size and parent roll type. An order is an incoming request for a certain amount of pounds of a particular SKU. A block will refer to a group of orders that are scheduled together and are made from the same parent roll. A run will designate a production occurrence, either of one SKU or of a block of product.

5.1 Input Requirements

A certain amount of information is supplied as input for scheduling decisions. Some of these inputs, known as product data, are historic, and stay constant for various runs. Order data can be updated dynamically, as it is dependent upon the incoming order file. Inputs may also be dependent upon the last run of the system and the current state of factory conditions, known as factory data. A summary list of data includes:

Figure 5.1

Scheduling System Operation



- A list of orders for the number of days being scheduled
- Beginning inventory levels for all SKUs
- Parent roll inventory levels
- A look-up table for setup times (from SKU# to SKU#)
- Information on average daily order amounts for each SKU
- A table of Physical Run Requirements for each SKU
- The capacity of the sheeters per day
- Production Rate (cutting speed) based on SKU
- The number of days which need to be scheduled

In the specific company studied, several other input tables were also necessary, but do not have a direct impact on specific scheduling issues. For example, a table that details the parent rolls for specific SKUs is needed. Weight of various paper grades is also required to determine the output in pounds of a specific production run.

5.2 Days of Demand Heuristic

The urgency that necessarily enters a system because of incoming orders is a major factor in considering the next product to schedule. In addition, each product's current inventory is also significant in insuring that a product is not produced when it still has a large backlog of finished goods. Although setup times are also important, it is apparent that most attempts to resolve this issue are thwarted by physical constraints. Therefore, a scheduling procedure was sought that could consider inventory and current demand as its two main influences.

These issues led to the use of a technique called the Days of Demand ratio. This ratio was formulated to give an indication of the Stock Keeping Unit that would run out of inventory the swiftest at present demand rates. SKUs could then be sequenced as a function of urgency, considering both due dates and inventory replenishment issues. There are strong similarities between the DOD ratio and an approach from Vergin and Lee (19), which used Economic Lot Sizing and examination of products that had less than a fixed number of days of inventory on hand.

Two pieces of information are necessary to compute the DOD ratio. The first is the pounds of the given SKU that are stored in inventory. The second is the demand for that product in the scheduling horizon. This demand must be a measurement of one day's needs, which can be calculated by two distinct methods. The first is to utilize only the demand for the SKU in the first scheduling day. The other method is to tally the demand for several days, and then divide by the number of days to get a measure of average daily demand.. The DOD ratio is then calculated by dividing present inventory levels by the measure of one day's demand, giving the number of days of demand that can be filled with the present amount of stored goods.

$$DOD\ Ratio = \frac{Inventory\ level\ of\ product\ i}{One\ day's\ demand\ of\ product\ i} \tag{5.1}$$

For example, consider the following orders received on 6/01/95:

SKU #	Order(Lbs)	Due Date	Daily Demand	Inventory Level	DOD Ratio
100	2,000 8,000	6/01/95 6/02/95	5,000	20,000	4.0
101	3,500	6/01/95	3,500	5,250	1.5
102	30,000 10,000	6/01/95 6/02/95	20,000	100,000	5.0

In this case, SKU 101 will be produced first, because it will run out of inventory the soonest. Although an order for product 100 is due on the same day, there is enough spare inventory to cover its demand for more days than 101. SKU 102 has a much larger order size, and is also due on the same date, yet also defers to product 101 because of the DOD ratio. In fact the size of the order and the due date are not considered independently, but rather only as a component of the DOD ratio.

The denominator in the DOD ratio is dependent upon the characteristics of the incoming order data. In the above example, the Average Demand used to calculate the ratio represents the average of the shown orders for each SKU. In this thesis, only the first day's demand was considered when computing the DOD ratio. Therefore, the ratio represents how quickly inventory will be depleted because of orders on the scheduling day.

There are cases where there will be ties between several products. For example, if the inventory of two SKUs with incoming orders has been depleted, their DOD ratios are equivalent. To break ties of this nature, the SKU with the greatest standard deviation in historic order size is scheduled first, because it is more likely that an unanticipated large order will arrive for that SKU. The decision to use this criteria was made as a function of customer service requirements.

5.3 Physical Run Requirements

In the studied facility, the physical requirements of the bulk parent rolls need to be considered when scheduling the individual products. Usually, five parent rolls are run simultaneously to take full advantage of the sheeter's capabilities. If each parent roll contains two tons of raw material, ten tons of finished product can be produced each time the sheeters are loaded. Because an order is usually in the range of one to two tons, the remaining roll capacity must be used to produce something else.

The sheeters are capable of cutting different size sheets from one parent roll. The machines must be slowed to allow the cutting knives to be moved, but the resultant setup time is much less than when an entire parent roll must be changed. This leads to the conclusion that when trying to utilize excess parent roll capacity, there are two options; produce more of the original product which triggered the run or produce SKUs of different sizes that can also be made from that parent roll.

In this scheduling system, this operation is performed by looking into the future for compatible orders. These "look-aheads" are of two varieties. The first type of look-ahead is for the same SKU number, which represents an identical product. The incoming order list for a designated number of days is examined in order to find this matching SKU. If more than one such order is found, each is inserted with the current order according to due date until the capacity of the parent roll is filled. Each time another order is inserted, the remaining capacity of the parent roll is examined. If there is remaining capacity, the look-ahead process continues until the capacity is used, or until the number of days to look ahead has been exhausted.

The second look-ahead is for orders with different SKU numbers but the same parent roll type, which means that their sheet dimensions are different. The procedure to do so is identical to that of the same SKU look-ahead, including the steps to recompute capacity and track scheduling days. The first type of look-ahead will be referred to as a "SKU-#" look-ahead, while the second type will be a "group-fill" look-ahead. Different look-ahead lengths will have various effects on scheduling dependent on the incoming order composite. The length of these look-aheads is a variable which will be discussed in the parameter tuning section of this thesis.

5.4 Economic Factors Satisfaction

In this particular implementation, Economic Run Lengths for most items tend to be in the range of 60,000 to 70,000 pounds of product. This number differs significantly from the average size of a Physical Run Requirement, which is usually in the neighborhood of 20,000 pounds. A method to balance these two numbers was necessary to produce an effective schedule.

Because the PRR is a hard constraint, production amounts must take it into consideration. As a lower bound, at least one PRR must always be produced. The term 'PRR multiple' will designate the number of multiples of a PRR that are being produced. Any run that is larger than one PRR must always be a multiple of it. Several strategies are available to attempt to reconcile this feature of the PRR with economic factors.

The first strategy is to produce the economic run length rounded to the nearest PRR. For example, if for a particular SKU, the ERL is 20,000 pounds and the PRR is 8,000 pounds, the two nearest PRR multiples would be 16,000 and 24,000 pounds, regardless of the actual order size. The ERL could be rounded up, to produce 24,000 pounds, which would represent three PRRs. It could also be rounded down, to produce 16,000 pounds, which would represent two PRRs. If the triggering order is larger than a single PRR, it will be necessary to produce at least the next lowest multiple of the PRR which is larger than the order size. This is not usually necessary, as most orders are much smaller in size than their respective PRRs.

Another strategy is to disregard the economic run length and produce the Physical Run Requirement that is nearest in size to the actual order amount. For example, if a SKU has an PRR of 8,000 pounds and an order is received for 3,500 pounds, the PRR amount will be produced, neglecting any ERL considerations. If the order was for 12,500 pounds, the nearest PRR multiples would be 8,000 pounds and 16,000 pounds. However, since the order is closest to the higher PRR multiple, 16,000 pounds would be produced. This is an attractive option because the ERL is only an approximation and this strategy retains quantities closer to the actual order.

These decisions are made based solely on the triggering order; the SKU type that is sequenced because of Days of Demand considerations. It must be decided if the order size will be rounded to the nearest PRR, or if a multiple of the PRR will be produced based on the economic run length of the specific SKU. Economic or physical requirements of other SKUs used to fill the parent roll capacity are disregarded. Once the total run amount has been determined for the triggering order, the look-aheads can be used to fill the remaining capacity.

In actuality, both the PRR and ERL amounts for a particular SKU are independent of the size of the incoming order of that product. The only exception to this rule is when the order size exceeds either the PRR, ERL, or both. In that case, it is necessary to produce at least the order quantity rounded up to the nearest parent roll.

5.5 Grouping Utilization

The proceeding sections have considered the basic order sequence and production quantities, but there are also grouping procedures and sheeter assignments that must be performed in order to guarantee tight setup times. A setup can be caused by several different factors, resulting in different setup times. For example, if several SKUs are being made from the same parent roll, the sheeter must be slowed between orders for about five minutes to move the cutting knives. When parent rolls are changed, a setup time of thirty minutes can result because of loading or unloading procedures.

After a basic sequence for a day is computed, the production list contains only blocks of product that need to be made. Each block represents a PRR multiple which has its excess capacity filled by other orders. The next step is to assign these blocks to one of the sheeters according to the remaining capacity of each sheeter in the scheduling period. A block will be assigned to the sheeter with the most remaining capacity. This is violated if there is already a block on the other sheeter which will cause a very low setup time between it and the block being added. For example, if the assignment is between sheeter one which has more capacity, or sheeter two, whose last block was from the same type of parent roll, the second sheeter will be chosen. This is continued until one day's capacity is filled on both sheeters. Before the next day's capacity is considered, a grouping procedure is enacted.

The grouping procedure consists of two separate tasks. The first is to sort between blocks. If any block was added to a sheeter because there was already another block using the same parent type present, the two blocks should be moved so that they are adjacent. The second grouping task is within blocks. Because the due date only specifies a day, moving product about within a days's schedule will not affect the satisfaction of that due date. Any members of the block which are from the same SKU should be made sequentially. Finally, the sequence should be placed in order of decreasing sheet width because this type of move is easier for the sheeters to accomplish. These procedures can be accomplished through a sorting algorithm, which usually can be effectively done with minimal computational requirements.

5.6 Rolling Horizon Scheduling

In most businesses, orders can be placed several days or weeks ahead of their due date. This demand is dynamic, in that orders are recieved continuously and do not arrive simultaneously. If simultaneous, or static arrivals occurred, all orders could be considered by the scheduling method, and concurrently sequenced for multiple time periods. However, such a schedule would neglect orders that are received after the sequencing process.

It is also impossible, for practical reasons, to update the schedule every time an order is received. Because a certain amount of time is needed to prepare raw goods and machines for the next scheduled product, having continuous updates would upset shop floor operation. Preemption, or removing a product during operation to work on a more urgent job is also precluded in this company by the restrictions of the parent rolls.

The means to review scheduling decisions on a periodic basis, yet not so often as to disrupt normal factory operations is by utilizing a rolling horizon (2). Every morning, the scheduling system is run, using the current input of orders. The resulting sequence may be for a number of days, but only the first of these days is implemented. The process is repeated for the following day's production, but not until the following morning. Any products which were scheduled, but not produced, are re-introduced on the following day as any other order would be.

5.7 Output Generation

Controlling the output is important for both scheduling purposes and for the analysis of the quality of a schedule. A sequence of orders should be given for each day for each machine. Setup time should be gathered as one measure of sequence quality. Inventory levels can also be tracked, to ensure that the schedule is not minimizing setups at the expense of overstock in inventory. A final output should be the number of late orders, their respective order amounts, and the number of days which they are late.

The combination of these factors allow us to assess the quality of the scheduling parameters, according to our criteria of minimizing setup cost, holding cost, and lateness. Because it is difficult to gauge the optimal solution in this case, the relative performance of these measures make it possible to tune the system to produce the best current strategy.

CHAPTER 6

System Performance

This chapter will detail the actual operation of the proposed scheduling algorithm, addressing the manner in which the various system components interact. Performance bounds will be detailed, addressing operation time and the number of elementary operations which are performed. Finally, comparison to previous techniques used by the studied company will be shown.

6.1 Algorithmic Approach

A graphical representation of system operation is portrayed in Figure 6-1. This has been provided to supplement this verbal description of operation.

The system operates in a way that utilizes both the Days of Demand ratio and certain variables that are designated by the user. The input files are read, and the DOD ratios are calculated for each SKU. The product with the lowest DOD ratio is selected first and is designated as the triggering order for a block of product. The Physical Run Requirements for that SKU is read, as well as the Economic Run Length strategy, look-ahead lengths, and the actual days which are to be scheduled. The PRR is converted to a PRR multiple dependent upon the ERL strategy. (Round up from the ERL, round down from the ERL, or approximate the triggering order.) The PRR multiple, or block size, consists of the triggering order plus remaining parent roll capacity.

A look-ahead procedure is then initiated, which searches into future

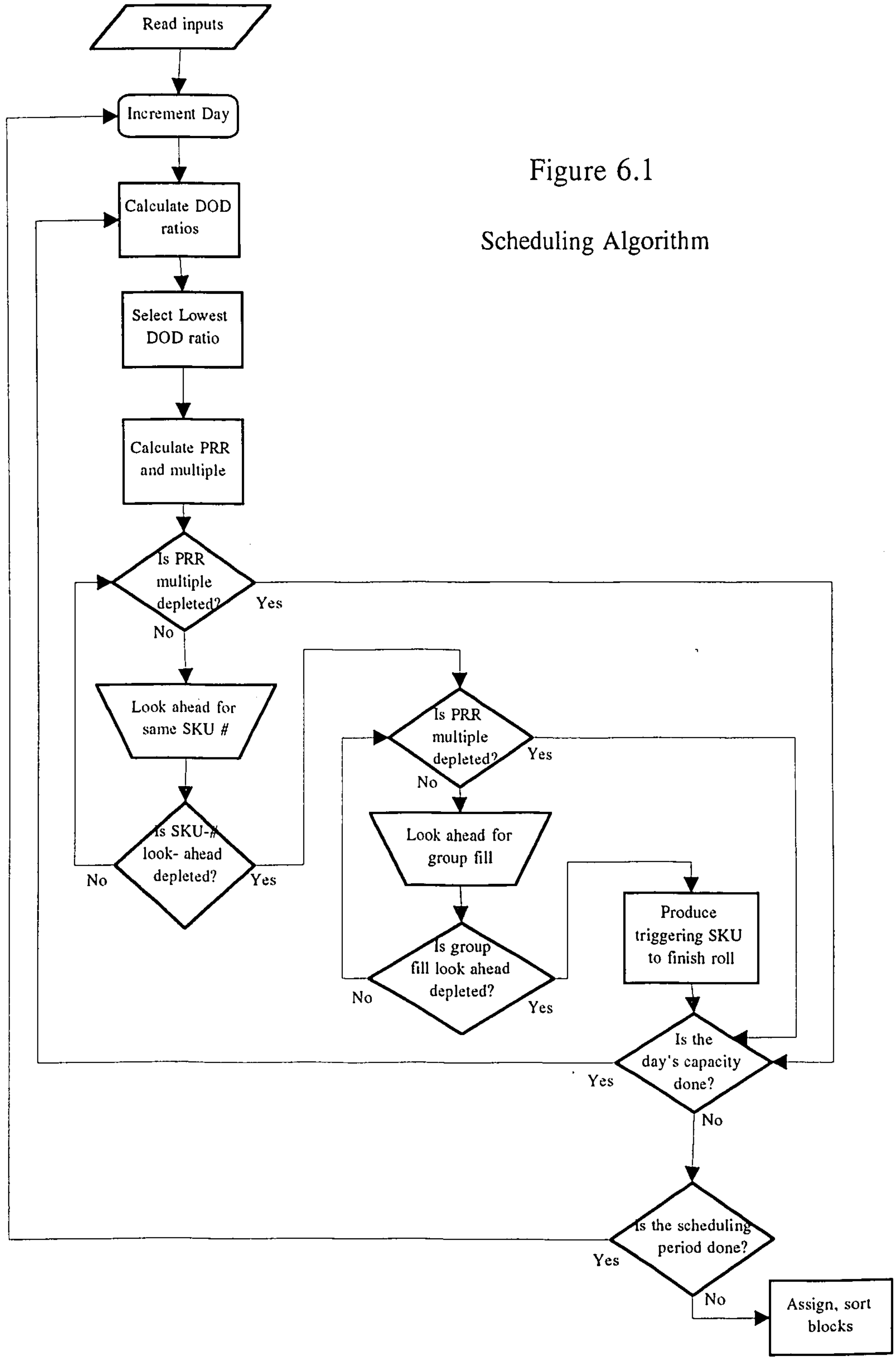


Figure 6.1

Scheduling Algorithm

orders for one with the same SKU number as the triggering order. The number of days of this look-ahead is a variable which is input by the user. Orders are added to the block until the capacity of the parent rolls are exceeded or until there are no more days in the look-ahead.

If capacity still exists, the second look-ahead procedure is initiated. It behaves in an identical matter to the first look-ahead, except that it searches for different SKUs which are made from the same parent roll as the triggering order. If the days are again exhausted before parent roll capacity is depleted, enough extra product of the triggering SKU is made to finish the roll. In Figure 6-1, these look-aheads are represented by internal looping until both PRR multiples and look-aheads are depleted.

Finally, when an entire block has been constructed and sequenced, DOD ratios are recalculated to recognize that the production of some orders may have changed that SKU's ratio. The system then moves to the SKU with the next lowest DOD ratio and repeats these procedures. For most products, the DOD ratio will not have changed, as no new orders have entered the system. However, if some orders for a particular SKU were satisfied by the previous parent roll's remaining capacity, ratios will be updated.

As the system continues, an initial sequence of products is constructed, and machine capacity is tracked so that the system will know when there is no more time in the scheduling period for production. The initial sequence will be altered by both an elementary assignment method and a sorting procedure.

The first will operate between blocks, while the second will operate within blocks of product.

The assignment needs to split groups between the two sheeters. Days are examined incrementally, and blocks are added to a sheeter according to remaining daily capacity. This is only violated to keep successive groups with identical parent rolls together. When one day's limit is exceeded, the entire exceeding block is scheduled on the that sheeter and any runover is subtracted from the next day's capacity. The next day is then considered. Sorting procedures are performed only within each day's sequence.

The sort is based on setup times, although as previously mentioned, it does not attempt to optimize the sequence. Instead, it groups any products with identical SKUs together and then arranges all members of a group according to their specific paper widths. Each individual day is sorted separately until the number of days that was to be scheduled has been completed.

At the end of the scheduling period, inventory files for both finished goods and parent rolls need to be updated. Other input files, such as ERL amounts, need to be updated periodically dependent upon historic order information. This provides correct beginning information for the next scheduling run. Because this scheduling system is a model of actual factory operation, it may be that because of downtime or other factors, the scheduled sequence does not match actual production. In such a case, input files should be altered to reflect actual factory conditions, rather than the results of the previous scheduling system run.

6.2 Production Example

A small example of how the system operates will now be presented. It is representative of actual order data, although some components have been altered to provide conditions that demonstrate effective operation. It is also assumed that we will place all orders on one sheeter.

The raw sequence is shown in Figure 6-2. It represents a list of incoming orders and their respective product specifications, as well as due date and inventory information. For this example, it is assumed that the DOD ratio will use incoming orders for only the first day in computation and only orders from the that day can trigger a group. In addition, the scheduling strategy will be PRR Order, and both look-aheads will be three days. The initial DOD ratio for the eligible SKUs has been computed in Figure 6-3. These products have also been sorted according to increasing order of the DOD ratio.

SKU #	Due Date	PR Type	Length	Width	Lbs order
161	7/1/93	L	25	38	7840
162	7/1/93	L	19	25	1600
166	7/1/93	L	19	25	2560
203	7/1/93	M	26	40	13192
537	7/1/93	R	25	38	5120
553	7/1/93	D	25	38	4915
556	7/1/93	R	23	35	2611
556	7/1/93	R	23	35	2611
556	7/1/93	R	23	35	2611
666	7/1/93	C	25	38	10080
666	7/1/93	C	25	38	2520
679	7/1/93	F	23	35	4787
695	7/1/93	F	24	36	2336
161	7/2/93	L	25	38	2560
537	7/2/93	R	25	38	2560
556	7/2/93	R	23	35	2611
661	7/2/93	C	19	25	2304
694	7/2/93	F	23	29	2329
697	7/2/93	F	23	29	10000
203	7/3/93	M	26	40	3360
666	7/4/93	C	25	38	2520

Figure 6.2
Raw Order Sequence

SKU #	Due Date	PR Type	Length	Width	Lbs order	Inventory	DOD ratio	PRR
161	7/1/93	L	25	38	7840	12000	1.53	14920
666	7/1/93	C	25	38	10080	21050	1.67	19326
679	7/1/93	F	23	35	4787	13100	2.74	19863
537	7/1/93	R	25	38	5120	14700	2.87	19715
553	7/1/93	D	25	38	4915	15200	3.09	16630
203	7/1/93	M	26	40	13192	41600	3.15	16974
556	7/1/93	R	23	35	2611	34570	4.41	21560
695	7/1/93	F	24	36	2336	12340	5.28	18864
166	7/1/93	L	19	25	2560	18750	7.32	16142
162	7/1/93	L	19	25	1600	13500	8.44	15015

Figure 6.3
DOD Ratio Sequence

The first triggering order that is scheduled is for SKU 161, which has a order on the first day for 7,840 pounds. The Physical Run Requirements for this SKU is 14,920 pounds. The look-ahead procedures are performed upon the order data from Figure 6-1 in order to fill the remaining 7,080 pounds of parent roll capacity that will remain after the triggering order is made. Although there are no other orders for SKU 161, there are three other products which utilize the L-type parent roll, which is the same one used by 161. The total pounds required by these three orders is 6,720, so they all can fit into the remaining parent roll capacity. The 360 pounds of unused parent roll capacity which remain after scheduling these orders is applied toward the inventory of the triggering SKU. This raises the production of the triggering order to 8200, represented by the following computation:

Physical Run Requirements	14920	
Triggering Order Size	- 7840	
Other Orders Using Same Parent Roll	- 6720	(6.1)
Excess of Triggering SKU	360	

DOD ratios are recomputed, which causes the ratios of products using the L parent roll to increase so that they are no longer urgent. The SKU with the next lowest DOD ratio is then examined and the process is repeated.

The result of the scheduling process can be seen in Figure 6-4. In this figure, the blocks of product that are made from one PRR are separated by blank lines. The triggering order is designated by an asterisk.

SKU #	Due Date	PR Type	Length	Width	Lbs order	Lb made	PRR
161*	7/1/93	L	25	38	7840	8200	14920
162	7/1/93	L	19	25	1600	1600	
166	7/1/93	L	19	25	2560	2560	
161	7/2/93	L	25	38	2560	2560	
666*	7/1/93	C	25	38	10080	11982	19326
666	7/1/93	C	25	38	2520	2520	
661	7/2/93	C	19	25	2304	2304	
666	7/4/93	C	25	38	2520	2520	
679*	7/1/93	F	23	35	4787	5198	19863
695	7/1/93	F	24	36	2336	2336	
694	7/2/93	F	23	29	2329	2329	
697	7/2/93	F	23	29	10000	10000	
537*	7/1/93	R	25	38	5120	6711	19715
556	7/1/93	R	23	35	2611	2611	
556	7/1/93	R	23	35	2611	2611	
556	7/1/93	R	23	35	2611	2611	
556	7/2/93	R	23	35	2611	2611	
537	7/2/93	R	25	38	2560	2560	
553*	7/1/93	D	25	38	4915	16630	16630
203*	7/1/93	M	26	40	13192	13614	16974
203	7/3/93	M	26	40	3360	3360	

Figure 6.4
Pre-sort Sequence

It is still necessary, however, to sort within the blocks to try to lower the collective setup time. This is done in compliance to the setup criteria of grouping those product with greater widths first, followed by those of less width. The sorted production sequence is shown in Figure 6-5. Triggering orders are still marked with asterisks, but they may not necessarily be the first product made in each block of product. Machine assignment and capacity was not considered in this example because this would have required too many products to provide a clear and concise sample.

6.3 Complexity Analysis

The complexity of this method was analyzed to determine bounds on its running time. This complexity is dependent upon several variables. These are the number of orders which need to be scheduled and the number of SKUs that the company has. The sorting and assignment procedures have been simplified to the extent that their complexity will not significantly add to the computational time of the entire system.

The DOD calculation is O(S), if *S* is the number of products the company has and O( ) signifies the number of elementary operations that must be performed for a particular calculation. The selection procedure of the minimum DOD ratio is O(1), as it is simply an identification of a minimum attribute. Adjustment of the PRR to the PRR multiple is also O(1), as it is a simple assignment. The look-ahead procedures are then initiated.

Each look-ahead procedure might have to examine every order in the

SKU #	Due Date	PR Type	Length	Width	Lbs order	Lb made	PRR
161*	7/1/93	L	25	38	7840	8200	14920
161	7/2/93	L	25	38	2560	2560	
162	7/1/93	L	19	25	1600	1600	
166	7/1/93	L	19	25	2560	2560	
666*	7/1/93	C	25	38	10080	11982	19326
666	7/1/93	C	25	38	2520	2520	
666	7/4/93	C	25	38	2520	2520	
661	7/2/93	C	19	25	2304	2304	
695	7/1/93	F	24	36	2336	2336	
679*	7/1/93	F	23	35	4787	5198	19863
694	7/2/93	F	23	29	2329	2329	
697	7/2/93	F	23	29	10000	10000	
537*	7/1/93	R	25	38	5120	6711	19715
537	7/2/93	R	25	38	2560	2560	
556	7/1/93	R	23	35	2611	2611	
556	7/1/93	R	23	35	2611	2611	
556	7/1/93	R	23	35	2611	2611	
556	7/2/93	R	23	35	2611	2611	
553*	7/1/93	D	25	38	4915	16630	16630
203*	7/1/93	M	26	40	13192	13614	
203	7/3/93	M	26	40	3360	3360	16974

Figure 6.5
Sorted Sequence

order list. This could involved examining all *N-1* orders other than the triggering order. If the DOD calculation is eventually performed after each one of the *N* orders, the complexity of the entire sequencing process is O(S*N*2(N-1)), which reduces to $O(SN^2)$.

6.4 Runtime Estimation

This system was implemented in C code and was tested on a model 486 PC. With the number of scheduling days equal to or less than thirty, the program ran in less than one minute on average. With the average number of orders per day in the range of 120, this represents the fulfillment of approximately 3600 orders, although relatively fewer required sequencing, due to the ability to fill from inventory in addition to filling from the sheeter.

6.5 Improvement over old system

It has been stated that it took up to three weeks to fill an incoming order under the studied company's old policies. In addition, the manual scheduling procedures could provide no more than small effort toward lowering setup time. Inventory was not tracked and the effects of scheduling upon it was never examined. Because the studied system is at a greenfield site and many traditionally ignored processes are considered to be important for the first time, their effect needs to be measured. However, there is a lack of hard economic or operational measures to compare with these effects.

While the techniques outlined in this thesis cannot promise to minimize any of these factors, they do provide an effective means to examine consequences and effects of the criteria upon the cost of a schedule. Different scenarios can be simulated to direct those factors which are variable toward levels that result in good output. In effect, a deterministic simulation can be performed upon historic data to measure the effects of different strategies.

The guarantee of three day delivery was met for 88 percent of the incoming orders in tests performed with this scheduling system. This criteria, however, is only one of those which were identified as important. Also, it represents an evaluation criteria (customer service) that is hardest to measure in absolute cost. Because tests were based on deterministic data, it cannot be stated that these results are representative of the general performance of the method. However, considering that it formerly took three weeks to deliver product, these results provide reassurance that the proposed strategy is valid. They also suggest a possibility of further improvement with relatively minor alterations.

Because inventory and setup costs were not previously quantified, their impact is difficult to gauge. The ability to simulate the different strategies and change input parameters becomes even more important in this situation. The company is able to examine what types of techniques are effective and will contribute to system operation.

Chapter 7

Parameter Investigation

The parameters, or input variables, used to schedule the system can greatly affect its efficiency and cost. Experiments were performed to determine which parameters work best for the criteria that were designated as important for this system. Although they relate directly to the specific operations of this problem, general observations can be made that also relate to other situations.

7.1 Parameter Selection and Representation

The number of days to be scheduled was held constant for the purpose of experimentation. In this manner, inventory levels, setup times, and due date satisfaction could be compared for an equal length of time. This period was selected to be thirty days, representing a month of production needs. Five months of data were available for testing.

Three parameters were selected that influence the quality of a schedule. The first of these is the economic scheduling strategy, which affects the size of the Parent Roll Requirements multiple. The second and third parameters deal with the number of days to perform SKU-# and group-fill look-aheads.

The justification for using the economic scheduling strategy has been described, but the impact that different strategies have upon system performance will also be considered. The scenario where the PRR Multiple is rounded up from the ERL quantity is known as PRR Up. PRR Down represents the PRR rounded down, and PRR Order signifies the PRR multiple closest to the triggering order size.

The resultant production amounts from PRR Up and PRR Down are very similar. The average Economic Run Length is approximately five to six times that of an average PRR. If this was the case for a particular SKU, PRR Up would result in six PRRs being produced, while PRR Down would result in five PRRs. Both these strategies represent production that involves a small number of setups and making large quantities from the same parent roll type sequentially.

PRR Order operates quite differently. Because most orders are one-fifth the size of a PRR for an SKU, the PRR multiple is usually only one. This strategy results in a larger number of setups, but production can occur in a much more flexible manner. Due dates can be met easier with this type of flexibility. The effective difference on inventory levels is also an issue, which will be evident in the experimental output. For example:

Order	*PRR*	*ERL*	*PRR Up*	*PRR Down*	*PRR Order*
2,000	10,000	55,000	60,000	50,000	10,000

This example shows the three economic strategies for a particular order based on it Physical Run Requirements.

The difference between the PRR strategies represents the difference between making to stock and making to order. PRR Order is very similar to making to order, because it tries to match the actual production amount and the order which triggers it. Although PRR Up and PRR Down can be likened to making to stock, in reality they represent a balance between making to stock and making to order. Because of the look-aheads for other products, a large amount of the triggering order that would normally completely enter inventory is split among other upcoming orders. Also, because production is sequenced according to the DOD ratio, the triggering orders are usually for very common product whose inventory will be depleted quickly.

The second parameter represents the look-ahead in the order file for SKUs of the same number as the triggering order. It was decided that the difference between a long look-ahead and a short look-ahead on sequencing should be examined. Since it had been decided that thirty days would be scheduled for experimental purposes, a short look-ahead was determined to be five days. A long look-ahead was determined to be twelve days. These numbers were selected based on observations of how often identical SKUs are ordered and on previous testing of system characteristics. It was observed that these settings would provide examples of representative situations.

The final parameter relates to the group-fill look-ahead for SKUs of different number which are made from the same parent roll as the triggering SKU. Again, only two factors are tested; a long look-ahead versus a short look-ahead. In this case, long and short have slightly different meanings than in the previous example. A short group-fill is only two days, while a long group-fill is seven days. There are likely to be more orders made from the same parent roll, when compared to the number of orders with the identical SKU number. Therefore, the group-fill look-aheads do not have to be as long as the SKU-# look-aheads to find an equivalent number of products. If ten product types can be produced from one parent roll, a search for nine of them will find more orders than a search for only the triggering SKU.

The resulting combination of variables can be seen in Figure 7-1. For each month of orders that were to be scheduled, twelve combinations needed to be considered (3 PRR strategies X 2 SKU look-aheads X 2 group-fill look-aheads). Five months of data were available, so the twelve possibilities were run for each month. This resulted in a total of sixty scheduling system runs.

7.2 Measurement System

The sum of inventory, setup, and lateness penalty costs was chosen to measure system performance. This measure represents the weighted priorities of the company according to the factors which add to the cost of a production schedule. Each cost had to be computed separately based on recorded performance measures and then summed aggregately.

To determine inventory costs, the average pounds in daily ending inventory was noted. This number was then multiplied by raw material cost per pound, by a daily interest rate representing holding costs, and by the thirty days in the month.

Scheduling Strategy

	PRR Down	PRR UP	PRR Round
Five[2]	Two[1] Seven	Two Seven	Two Seven
Twelve	Two Seven	Two Seven	Two Seven

[1] Internal numbers (two, seven) represent the group fill look-ahead length

[2] Left row headings (five, twelve) represent the identical SKU # look ahead length

Figure 7.1
Possible Combinations of Input Parameters

Setups were tracked by both the number of individual setups and the time it took to perform the setups. The second figure was to measure schedule cost because different types of setups can result in varying times, which would not be represented in the total number of setups. The number of setup minutes was then multiplied by production cost per minute on a sheeter.

Lateness penalty cost was more difficult to assess. The company might have to reduce their selling price by five to thirty percent, depending on how late the order is. An average of ten percent was assessed to account for the fact that although many late orders are several days late, most are only one day late, rounding the number more toward five than thirty percent.

These three factors; inventory, setup, and lateness cost correlate directly to the parameters of *a*, *b*, and *c* used in the mathematical function of Chapter 4. The combination of these factors represents a total cost for the schedule determined by the input parameters. In examination of output data, the numbers do not represent actual production cost to the studied company, but rather a figure to measure the relative strength of one schedule versus another. Due to proprietary reasons, some cost factors were altered in the shown examples, but they remain representative of actual figures.

7.3 Experimental Design

A full factorial design was run using the three parameters. This means that every possible combination of each factor was run versus all the other factors. Effects were fixed, because the levels of all factors were selected before experimentation. Months were used as a blocking factor, to account for the variation in orders in the five months that were used. Interactions were investigated in addition to main effects from the three basic factors.

Randomization was not used to determine the order in which experiments were performed. The program was not dependent upon a previous run, but rather, factory start-up conditions were assumed at each run. Therefore, output and sequencing was independent of the time order of the run. Randomization would not have contributed any significant effect to the process.

SAS (Statistical Analysis System) was used to perform the analysis of variance. Duncan's test was assumed to show a good representation of the differences between means of those effects that were significant. Residuals were plotted versus means, time, and predicted values. Output from the SAS program is available in Appendix B.

7.4 Results and Interpretation

The results of the schedule cost for each of the sixty runs can be seen in Figure 7.2. Among the input parameters, the effects from strategy and both look-aheads were significant in a statistical sense. In addition, the interaction between the scheduling strategy and both types of look-aheads also had a significant impact.

In the group-fill look-ahead, a longer time period resulted in a lower schedule cost. Intuitively, this makes sense as a longer look-ahead will result

Month	SKU # Look Ahead	Up 5	Up 12	Down 5	Down 12	Order 5	Order 12
June	2	211919	212484	184152	194193	201328	242105
	7	151294	161006	138223	157700	216733	245574
July	2	181978	171445	161924	169542	178598	238784
	7	123893	129705	123681	145421	202639	239086
August	2	232828	228595	188098	186445	235032	234546
	7	175556	171643	155600	172888	243296	274264
September	2	251128	251128	218129	243204	252001	267407
	7	190281	194062	183580	182352	244339	309615
October	2	215464	228758	183874	181996	216318	240320
	7	163137	160018	145599	168323	227569	256140

Scheduling Strategy: Up, Down, Order (Group Fill Look-ahead: 5, 12)

Figure 7.2
Experimental Results

in more 'real' orders being produced and less excess of the triggering SKU. Therefore, the needs of future time periods are reduced, while total inventory is also decreased because there is less product which is only made to finish the parent roll.

The SKU-# look-ahead also had a significant effect, but a longer look-ahead resulted in greater cost. This specific reason for this could have several explanations. An example might be the effect that a longer look-ahead has upon the group-fill look-ahead. For example, if the remaining parent roll capacity is used to satisfy the SKU-# look-ahead, the potential to produce some urgent orders that could utilize the same parent roll might be lost.

The strategy had a significant effect upon the outcome of the schedule. The PRR Down strategy produced the schedules with the lowest aggregate cost. Both PRR Down and PRR Up resulted in much better sequences than did PRR Order. This can probably be assessed to the increase in setup time when the PRR multiple was kept close to the triggering order. However, the fact that PRR Down performed better than PRR Up suggests that the cost function as compared to strategy is concave. This means that there is some point between PRR Order and PRR Up where cost could be minimized. However, this point will differ for each product, according to its particular PRR multiple.

Interactions between the economic strategy and both types of look-aheads were significant. Because the various strategies and look-aheads represent very different production quantities and product mixes, it understandable that there would be an interaction. This also makes sense when considering that these effects produced significant results on their own.

The settings which were chosen for investigation were justified by the experiments. Significant differences were shown to exist when parameters were set at levels which intuitively require different algorithmic behavior. Although the particular cost of a specific schedule will always be impacted by stochastic demand and factory conditions, observing parameter levels that provide consistently good schedules is important.

In summary, for the particular parameters that this experiment was investigating, it is possible to suggest a preferred combination. The strategy should be PRR Down, with the group-fill look-ahead set to long, and the SKU-# look-ahead set to short. These settings are suggested with the realization that further parameter tuning could provide better settings.

CHAPTER 8

Conclusions

The proposed system provides a method to produce feasible schedules while considering the multiple criteria of setup time, inventory cost, and due date satisfaction. The resultant schedules are not guaranteed to be optimal, but they do represent an attainable sequence which can be produced economically according to the technical capabilities of production machinery.

When tested with conditions that are representative of actual operation, the results suggest that this method provides schedules that are better than those produced by methods previously used at the test site. This technique will allow the tested company to increase flexibility and consider complex levels of operational factors simultaneously.

In the particular implementation relating to the studied facility, the system contained enough flexibility to allow for parameter tuning to occur. Therefore, operation could be simulated with actual order data to determine those settings which result in superior schedules.

This method was innovative because it measured the combined cost of lateness, setup, and inventory while considering the limiting effect of physical constraints. Also, scheduling was performed as a function of urgency of particular orders, as measured by the combination of inventory and due dates. No important criteria were neglected or assumed to be dominant to all others.

Rather, a balance was found by which practical operation was achieved.

Specification of the relative performance of this system versus other scheduling techniques was not within the scope of this thesis. In proving utility in a general sense, a method must be compared to other established techniques. Therefore, it cannot be concluded that this system is superior to others or that it will provide equally good results in other testing sites.

Such testing can be undertaken in many types of businesses where companies wish to consider the chosen objectives of setup, inventory, and due dates. The routines proposed in this thesis can be applied in many situations where a companies wish to consider more than one evaluation criteria. Success will be dependent upon the specific characteristics of each situation, and application must consider the particular constraints and product hierarchy which are present.

CHAPTER 9

Recommendations for Future Work

Although many of the pertinent issues related to the implementation of this scheduling strategy have been investigated, there are clearly other areas which are extensions of this technique and deserve further examination. Many of these improvements were out of the scope of this thesis, or address issues that were not critical to system goals in this case.

1. Comparison to other scheduling strategies.

Such a comparison is an effective method to prove the validity of the studied technique. There are many complex scheduling methods available, and their implementation in the outlined situation could be investigated. The effect on the composite criteria of lateness, setup times, and inventory levels should be measured, rather than a comparison of sequences. This type of study might not only prove the worth of the methods of this thesis, but investigation of the effects of other strategies on the three separate areas of the evaluation function might result in alterations to the tested heuristic that improve its efficiency. For example, if it was shown that another heuristic was very effective in meeting due dates, the methods of this thesis might borrow a piece of logic to achieve better due date satisfaction.

2. Relaxation of constraints

The constraints present in the studied company were instrumental in the formulation of a large amount of the scheduling logic. However, if these constraints did not exist, the scheduling algorithm would operate differently. In particular, the original sequence designated by the DOD ratios would remain constant, until more orders were entered into the system. Relaxation could give insight into areas where further emphasis should be placed.

3. DOD ratio computation

In the testing of this thesis, a particular form of the DOD ratio was utilized. It involved only using the orders of the first day in ratio calculation. However, it is also possible to examine orders for several days for a particular product, and divide by the number of days to get an average daily order size. In this case the ratio does not measure the depletion of inventory for the first scheduling day, but rather for the number of examined days. This change would create a significant variation in DOD ratio order, and affect whether certain orders miss or meet their deadlines.

4. Non-regular inventory items

A large concern to the studied company are those products which are not regular inventory items, known as Special Making Orders. (SMOs) These type of orders add additional complexity to sequencing discussions. SMOs represent strange sheet dimensions that can otherwise be cut out of standard parent roll types. They usually are very urgent, however, because there is never a supply of these products in inventory. Their integration into the schedule would be interesting, as they would in effect have a constant DOD ratio of zero. In system testing, the percentage of orders that SMOs usually represent was subtracted from sheeter capacity in order to retain normal production capabilities.

5. Tie breaking procedures.

The tie-breaking procedure used in this thesis when two SKUs had identical DOD ratios was to schedule the order which had greater variability in historic orders. However, this does not take into effect the size of the current order or the urgency of the present scheduling decisions. Several other methods could be utilized as tie-breakers, such as length of the PRR for each product, or the difference in a myopic cost measurement. The factor which was used, variability, attempts to offset the possibility of a large incoming urgent order. Due dates and order size should also be examined to ensure the true necessity of each order.

6. Parent roll capacity fulfillment.

The method to fill remaining parent roll capacity after both look-ahead procedures are completed also deserves investigation. Merely filling out the roll with more of the triggering order does not necessarily make sense, if that order is for a very uncommon product. If all SKUs that make up the product block were examined, the one with highest average demand could be made instead, because extra inventory for that SKU would be most useful. Otherwise, the SKU in the block with the largest volume could be made, to reduce setup times.

Chapter 10

Summary

A scheduling method was presented that is an effective means to schedule according to the urgency of particular items. Scheduling issues were examined and a model was formulated that could be tested in a paper production facility. This method attempts to meet three objectives with somewhat conflicting emphasis: minimization of setup times, due date satisfaction and minimization of inventory costs. The main technique used to do so is known as the Days of Demand ratio.

The needs of the particular company were assessed to determine the motivation for system development. Historic factory operation was examined, and areas of emphasis were chosen. Several goals were set: 1) formulation of a multi-criteria evaluation function, 2) satisfaction of physical constraints, and 3)a feasible production sequence as a function of urgency.

A literature survey was performed to provide background methodologies and highlight areas where innovation could occur. Successful methods were noted so that they could be used as references in the development of techniques.

Analysis was performed to determine system needs. Requirements were outlined and factors which affect system design were delineated. System design occurred as a function of the indicated requirements and progression toward performance goals. Data from the company was then used to test the system. Iterative improvements were made until numerical validity was achieved. Finally, parameters were tested to determine good settings and verify intuitive decisions about system operation. Conclusions about the applicability of the chosen method and the possibility of future extensions were made.

In this manner, a feasible system for the production of schedules was formulated and tested. Utilizing the Days of Demand ratio and constraint-based priority rules proved to be effective when tested in the studied company.

List of References

1. Baker, Kenneth R., "An Experimental Study of the Effectiveness of Rolling Schedules in Production Planning" Decision Science, Vol. 8 (1977), pp. 19-20

2. Baker, Kenneth R., and Peterson, David W., "An Analytic Framework for the Evaluation of Rolling Schedules" Management Science, Vol. 25 (1979), pp. 341-351

3. Bernardo, John, and Lin, Kun-Si, "An interactive procedure for Bi-Criteria Production Scheduling" Computers and Operations Research, Vol. 21 (1994), pp. 677-688

4. Cheng, T.C.E., and Sin, C.C.S., "A State of the Art Review of Parallel Machine Scheduling Research" European Journal of Operations Research, Vol. 47 (1990), pp. 271-292

5. Fry, T., Armstrong, R., and Lewis, H, "A Framework for Single Machine Multiple Objective Sequencing Research" OMEGA Vol. 17 (1989), pp. 595-607

6. Gupta, Sushil, and Kyparisis, Jerzy, "Single Machine Scheduling Research" OMEGA Vol. 15 (1987), pp. 207-227

7. Haynes, R.D., Komar, C.A., and Byrd, Jack, "The Effectiveness of Three Heuristic Rules for Job Sequencing in a Single Production Facility" Management Science, Vol. 19 (1973), pp. 575-580

8. Johnson, S.M., "Optimal Two and Three-Stage Production Schedules with Setup Times Included" Naval Research Logistics Quarterly, Vol. 1 (1954), pp. 61-68

9. Leachman, Robert, and Gascon, Andre, "A Heuristic Scheduling Policy for Multi-Item, Single-Machine Production Systems with Time-Varying Stochastic Demands" Management Science, Vol. 34 (1988), pp. 377-390

10. Liao, C., Huang, R., and Tseng, S., "Use of Variable Range in Solving Multiple Criteria Scheduling Problems" Computers and Operations Research, Vol. 19 (1992), pp. 453-460

11. Lofti, V., and Yoon, Y.S., "An Algorithm for the Single-Item Production Problem with Concave Production and Holding Costs", Journal of the Operational Research Society, Vol. 45 (1994), pp. 934-941

12. MacCarthy, B.L., and Liu, Jiyin, "Addressing the Gap in Scheduling Research: A Review of Optimization and Heuristic Methods in Production Scheduling", Intl. Journal of Production Research, Vol. 31 (1993), pp. 59-79

13. Magee, J.F., and Boodman, D.M., Production Planning and Inventory Control, New York: McGraw Hill, 1967. p. 151

14. Morton, Thomas, and Pentico, David, Heuristic Scheduling Systems, New York: John Wiley & Sons, 1993. pp. 61-67, 241

15. Parker, G., and Rardin, R., Discrete Optimization, Boston: Academic Press, 1988. pp. 11-51

16. Sen, T. and Gupta, Sushil, " A State-of-the-Art Survey of Scheduling Research Involving Due Dates" OMEGA, Vol. 12 (1984), pp. 63-76

17. Smith, W.E., "Various Optimizers for Single Stage Production" Naval Research Logistics Quarterly, Vol. 3 (1956), pp. 59-66

18. Tsubone, H., Ohba, M., Takamuki, H., and Miyake, Y., "A Production Scheduling System for a Hybrid Flow Shop - A Case Study" OMEGA, Vol. 21 (1993) pp. 205-214

19. Vergin, Roger and Lee, Terry, " Scheduling Rules for the Multiple Product Single Machine System with Stochastic Demand" Infor, Vol. 16 (1978), pp. 64-73

20. Wah, B.M. and Baumgarter, K.M., "Computer Scheduling Algorithms: Past, Present, and Future" Information Sciences, Vol. 57-58 (1991), pp. 319-345

Appendix A

Experimental Output from SAS

```
                    The SAS System                      1
                           02:35 Thursday, December 15, 1994

         General Linear Models Procedure
             Class Level Information

      Class      Levels    Values

      MONTH           5    Aug Jul Jun Oct Sep

      LOOKAHED        2    5 12

      GROUPFIL        2    2 7

      RUNTYPE         3    Down Order Up

     Number of observations in data set = 60
```

General Linear Models Procedure

Dependent Variable: SCH_COST

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	29	98312995966	3390103309	44.71	0.0001
Error	30	2274478830	75815961		
Corrected Total	59	100587474796			

R-Square	C.V.	Root MSE	SCH_COST Mean
0.977388	4.333058	8707.2361	200949.00

Source	DF	Type I SS	Mean Square	F Value	Pr > F
MONTH	4	23103305686	5775826421	76.18	0.0001
LOOKAHED	1	3535227856	3535227856	46.63	0.0001
GROUPFIL	1	9387654267	9387654267	123.82	0.0001
RUNTYPE	2	44401051695	22200525847	292.82	0.0001
MONTH*LOOKAHED	4	367974414	91993604	1.21	0.3258
MONTH*GROUPFIL	4	255933957	63983489	0.84	0.5085
MONTH*RUNTYPE	8	987271286	123408911	1.63	0.1586
LOOKAHED*GROUPFIL	1	180946774	180946774	2.39	0.1329
LOOKAHED*RUNTYPE	2	2626315130	1313157565	17.32	0.0001
GROUPFIL*RUNTYPE	2	13467314902	6733657451	88.82	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
MONTH	4	23103305686	5775826421	76.18	0.0001
LOOKAHED	1	3535227856	3535227856	46.63	0.0001
GROUPFIL	1	9387654267	9387654267	123.82	0.0001
RUNTYPE	2	44401051695	22200525847	292.82	0.0001
MONTH*LOOKAHED	4	367974414	91993604	1.21	0.3258
MONTH*GROUPFIL	4	255933957	63983489	0.84	0.5085
MONTH*RUNTYPE	8	987271286	123408911	1.63	0.1586
LOOKAHED*GROUPFIL	1	180946774	180946774	2.39	0.1329
LOOKAHED*RUNTYPE	2	2626315130	1313157565	17.32	0.0001
GROUPFIL*RUNTYPE	2	13467314902	6733657451	88.82	0.0001

General Linear Models Procedure

Duncan's Multiple Range Test for variable: SCH_COST

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 30 MSE= 75815961

Number of Means	2
Critical Range	4591

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	GROUPFIL
A	213457	30	2
B	188441	30	7

General Linear Models Procedure

Duncan's Multiple Range Test for variable: SCH_COST

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 30 MSE= 75815961

Number of Means	2	3
Critical Range	5623	5910

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	RUNTYPE
A	238285	20	Order
B	190316	20	Up
C	174246	20	Down

General Linear Models Procedure

Duncan's Multiple Range Test for variable: SCH_COST

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 30 MSE= 75815961

Number of Means 2
Critical Range 4591

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	LOOKAHED
A	208625	30	12
B	193273	30	5

Univariate Procedure

Variable=RESID

Moments

N	60	Sum Wgts	60
Mean	0	Sum	0
Std Dev	6208.904	Variance	38550489
Skewness	0.251401	Kurtosis	0.597524
USS	2.2745E9	CSS	2.2745E9
CV	.	Std Mean	801.5661
T:Mean=0	0	Pr>|T|	1.0000
Num ^= 0	60	Num > 0	27
M(Sign)	-3	Pr>=|M|	0.5190
Sgn Rank	-24	Pr>=|S|	0.8615
W:Normal	0.978017	Pr<W	0.5947

Quantiles(Def=5)

100% Max	16436.73	99%	16436.73
75% Q3	3370.4	95%	11198.78
50% Med	-500.733	90%	7827.692
25% Q1	-3206.48	10%	-8418.01
0% Min	-14212.5	5%	-11011.2
		1%	-14212.5
Range	30649.25		
Q3-Q1	6576.875		
Mode	-14212.5		

7

Extremes

Lowest	Obs	Highest	Obs
-14212.5(	40)	9289.733(	32)
-11794.3(	38)	10881.68(	51)
-11698.4(	26)	11515.88(	37)
-10324(	20)	15476.65(	14)
-9667.53(	47)	16436.73(	41)

Univariate Procedure

Variable=RESID

```
Stem Leaf                     #             Boxplot
  16 4                        1                0
  14 5                        1                0
  12
  10 95                       2                |
   8 03                       2                |
   6 07                       2                |
   4 125001                   6                |
   2 0259035                  7             +-----+
   0 589903                   6             |  +  |
  -0 73008866411             11             *-----*
  -2 7422184442              10             +-----+
  -4 505                      3                |
  -6 21                       2                |
  -8 780                      3                |
 -10 873                      3                |
 -12
 -14 2                        1                0
     ----+----+----+----+
 Multiply Stem.Leaf by 10**+3
```

```
                         Normal Probability Plot
  17000+                                                    *
       |                                                *   +++
       |                                                  +++
       |                                               **++
       |                                            +*++
       |                                         +***
       |                                      +****
       |                                   ****
   1000+                               +****
       |                            *****
       |                       *****
       |                     **++
       |                  +*+
       |              ++***
       |           *+**
       |       +++
 -15000+++*
       +----+----+----+----+----+----+----+----+----+----+
           -2        -1         0        +1        +2
```

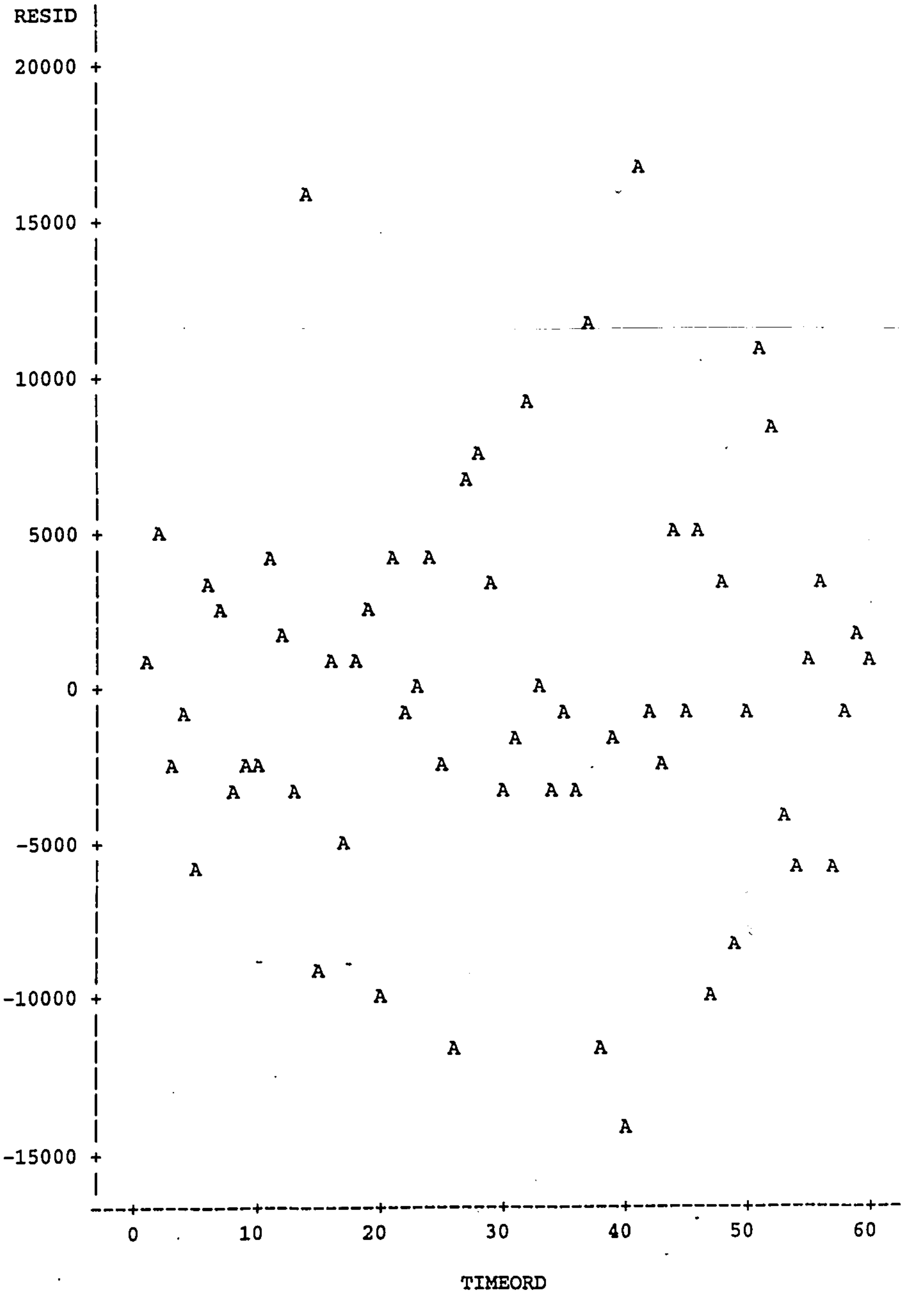
Univariate Procedure

Variable=RESID

Frequency Table

		Percents				Percents	
Value	Count	Cell	Cum	Value	Count	Cell	Cum
-14212.5	1	1.7	1.7	-446.1	1	1.7	51.7
-11794.3	1	1.7	3.3	-133.95	1	1.7	53.3
-11698.4	1	1.7	5.0	-113.767	1	1.7	55.0
-10324	1	1.7	6.7	450.3167	1	1.7	56.7
-9667.53	1	1.7	8.3	798.0167	1	1.7	58.3
-8807.15	1	1.7	10.0	876.7333	1	1.7	60.0
-8028.87	1	1.7	11.7	921.9667	1	1.7	61.7
-6168.52	1	1.7	13.3	1040.567	1	1.7	63.3
-6050.43	1	1.7	15.0	1250.683	1	1.7	65.0
-5511.18	1	1.7	16.7	2021.217	1	1.7	66.7
-5018.68	1	1.7	18.3	2211.733	1	1.7	68.3
-4460.18	1	1.7	20.0	2547.233	1	1.7	70.0
-3700.07	1	1.7	21.7	2931.517	1	1.7	71.7
-3390.77	1	1.7	23.3	2964.067	1	1.7	73.3
-3213.52	1	1.7	25.0	3271.483	1	1.7	75.0
-3199.43	1	1.7	26.7	3469.317	1	1.7	76.7
-3141.7	1	1.7	28.3	4107.85	1	1.7	78.3
-2783.78	1	1.7	30.0	4248.983	1	1.7	80.0
-2412.18	1	1.7	31.7	4464.133	1	1.7	81.7
-2369.02	1	1.7	33.3	4977.067	1	1.7	83.3
-2350.98	1	1.7	35.0	5025.067	1	1.7	85.0
-2166.77	1	1.7	36.7	5108.817	1	1.7	86.7
-1707.02	1	1.7	38.3	7013.267	1	1.7	88.3
-1348.82	1	1.7	40.0	7704.317	1	1.7	90.0
-985.683	1	1.7	41.7	7951.067	1	1.7	91.7
-966.933	1	1.7	43.3	9289.733	1	1.7	93.3
-832.517	1	1.7	45.0	10881.68	1	1.7	95.0
-798.933	1	1.7	46.7	11515.88	1	1.7	96.7
-597.017	1	1.7	48.3	15476.65	1	1.7	98.3
-555.367	1	1.7	50.0	16436.73	1	1.7	100.0

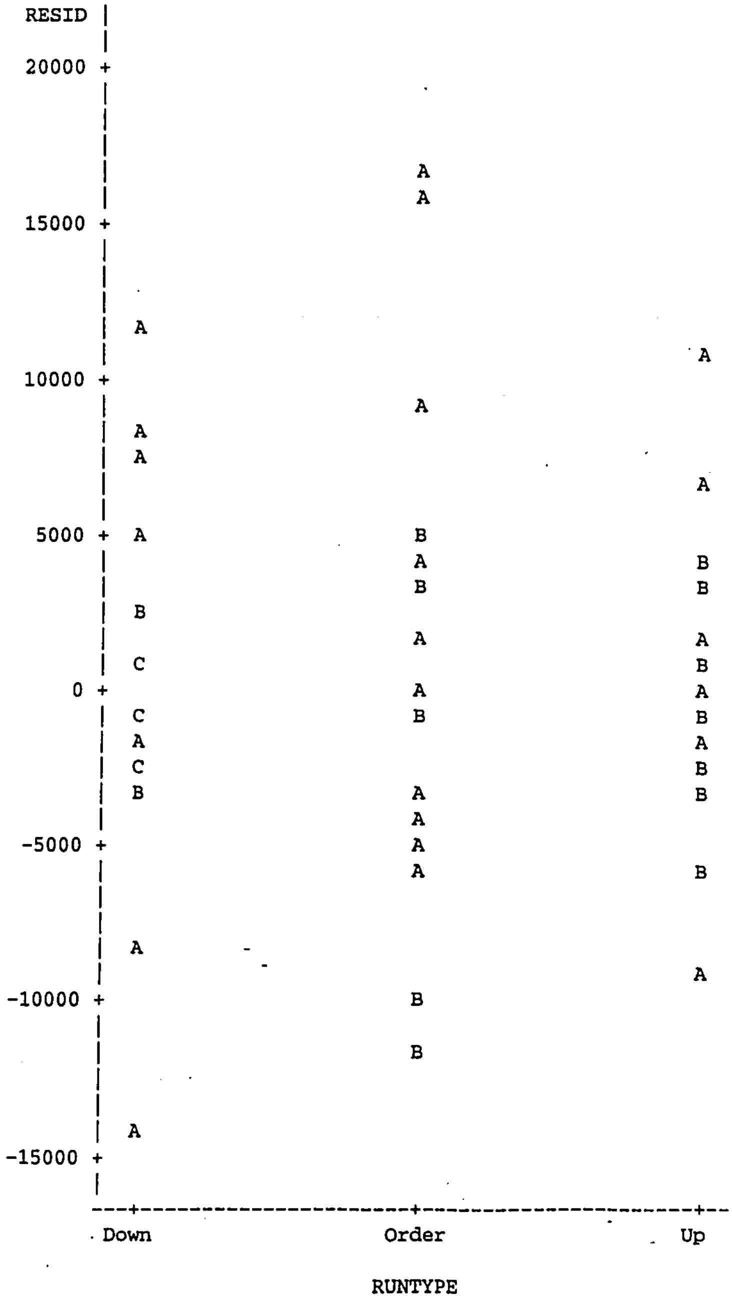
Plot of RESID*TIMEORD. Legend: A = 1 obs, B = 2 obs, etc.



```
Plot of RESID*LOOKAHED.  Legend: A = 1 obs, B = 2 obs, etc.

  RESID |
        |
  20000 +
        |
        |
        |
        |                                                  A
        |                                                  A
  15000 +
        |
        |
        |
        |                                                  A
        |                                                  A
  10000 +
        |  A
        |                                                  A
        |                                                  A
        |                                                  A
        |
   5000 +  B                                               A
        |  C
        |  B                                               B
        |  B
        |  B
        |  B                                               C
      0 +  B
        |  D                                               C
        |  A                                               A
        |  C                                               B
        |  C                                               B
        |                                                  A
  -5000 +                                                  A
        |  A                                               B
        |
        |
        |                                                  A
        |                                                  A
 -10000 +  B
        |
        |                                                  B
        |
        |
        |                                                  A
 -15000 +
        |
        ---+-----------------------------------------------+--
           5                                               12

                                LOOKAHED
```

```
Plot of RESID*GROUPFIL.  Legend: A = 1 obs, B = 2 obs, etc.

 RESID |
       |
 20000 +
       |
       |
       |
       |                                                A
       |  A
 15000 +
       |
       |
       |
       |  A
       |  A
 10000 +
       |  A
       |                                                A
       |                                                A
       |  A
       |
  5000 +  B                                             A
       |  A                                             B
       |  A                                             C
       |  B
       |                                                B
       |  B                                             C
     0 +  A                                             A
       |  B                                             E
       |  B
       |  D                                             A
       |  B                                             C
       |                                                A
 -5000 +                                                A
       |  A                                             B
       |
       |
       |  A
       |  A
-10000 +  A                                             A
       |
       |  B
       |
       |
       |                                                A
-15000 +
       |
       ---+-----------------------------------------------+--
          2                                               7

                              GROUPFIL
```

Plot of RESID*RUNTYPE. Legend: A = 1 obs, B = 2 obs, etc.

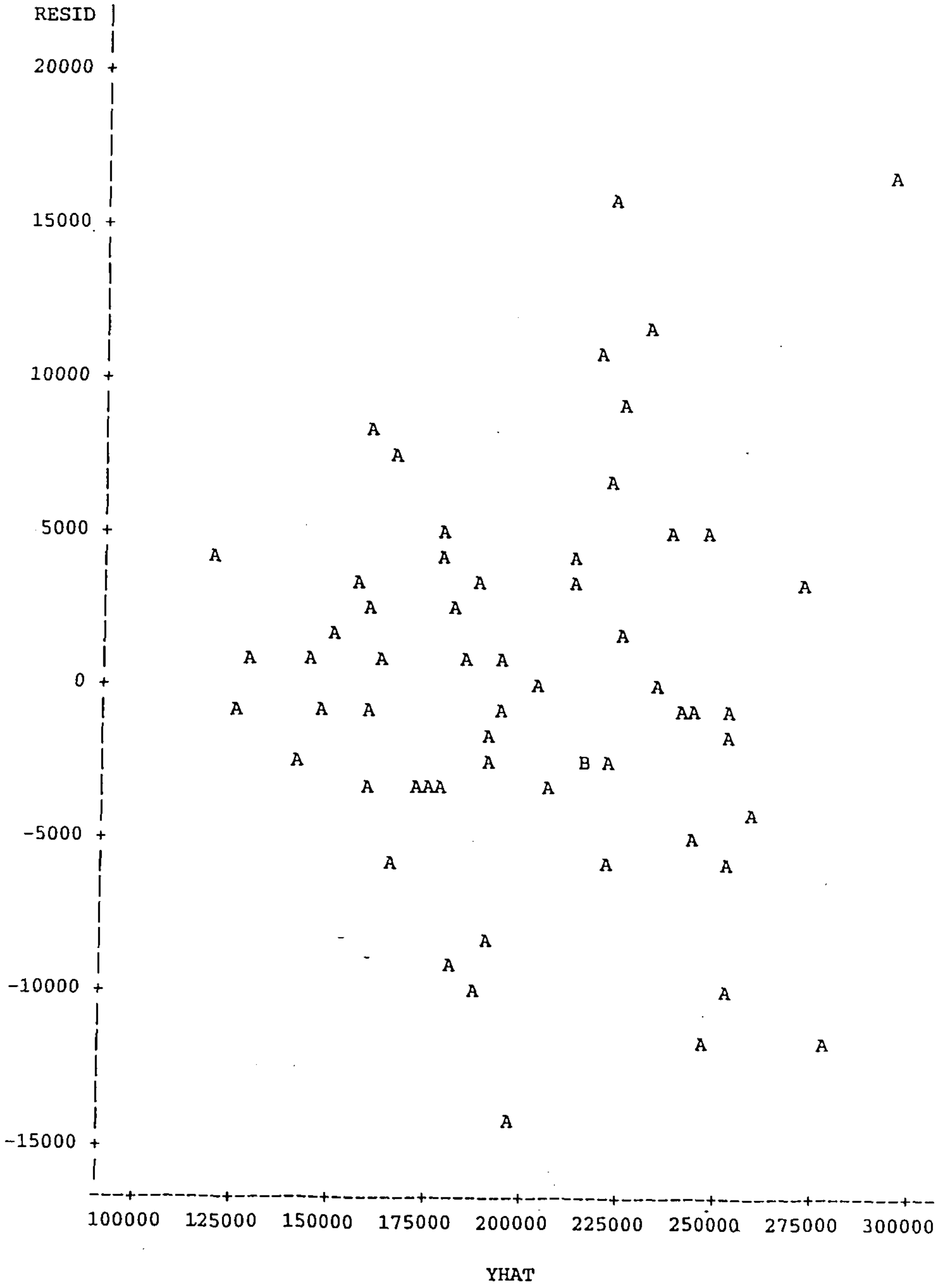


residual vs Month - thesis program 13
02:35 Thursday, December 15, 1994

Plot of RESID*MONTH. Legend: A = 1 obs, B = 2 obs, etc.

```
  RESID |
        |
  20000 +
        |
        |
        |
        |                                                          A
        |                A
  15000 +
        |
        |
        |
        |                                                          A
        |                                            A
  10000 +
        |  A
        |                                            A
        |  A
        |  A
        |
   5000 +                              A                           B
        |                B             A
        |  A                           A             A             A
        |                A             A
        |                              A             A
        |                B             A             B
      0 +  A             A
        |  A             A             A             B             B
        |  A                                                       A
        |  A                           C                           A
        |  C             A             A
        |                                            A
  -5000 +                A
        |                              A             B
        |
        |
        |                                            A
        |                A
 -10000 +                A                                         A
        |
        |  A                                                       A
        |
        |
        |                                                          A
 -15000 +
        |
        ---+-------------+-------------+-------------+-------------+--
          Aug.          Jul           Jun           Oct           Sep

                                     MONTH
```

Plot of RESID*YHAT. Legend: A = 1 obs, B = 2 obs, etc.



Vita

Robert D. Mallon was born in Elizabeth, New Jersey on September 29, 1971 to John and Mary Ann Mallon. He attended Lehigh University, receiving a Bachelor of Science in Industrial Engineering in May, 1993. During that time, Robert was the president of the Alpha Pi Mu IE Honor Society, a member of the Tau Beta Pi Engineering Honor Society, and was recognized as the outstanding Industrial Engineer in both his Junior and Senior years. Robert remained at Lehigh for graduate school, studying under a Gotshall Fellowship and graduating in May of 1995.

END OF TITLE